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NRL SSD Research Achievements: 2000–2010

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14. ABSTRACT
The 2000s were banner years for the Naval Research Laboratory (NRL) Space Science Division (SSD), with participation in several major space experiments. This summary provides a technical overview of some of the significant NRL SSD research achievements during this decade, 2000-2010.

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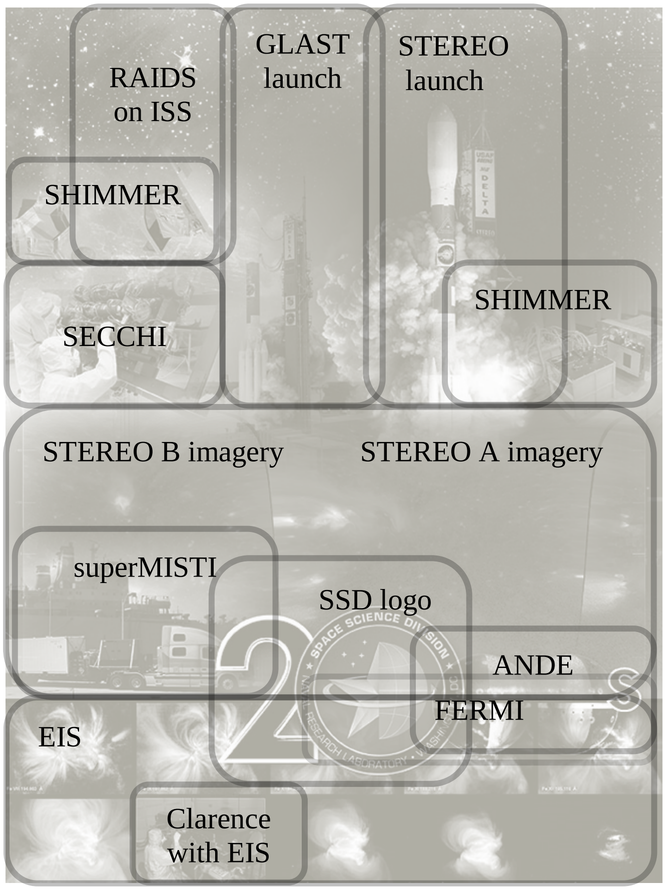

The 2000's were banner years for the Naval Research Laboratory (NRL) Space Science Division (SSD), with participation in several major space experiments and associated scientific research. First the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument suite of coronagraphs and extreme-ultraviolet imagers was launched in 2006 on the twin NASA Solar Terrestrial Relations Observatory (STEREO) spacecraft. The two spacecraft are now orbiting on the far side of our star, enabling simultaneous views of the entire Sun for the first time in solar observational history. Second, the Extreme Ultraviolet Imaging Spectrometer (EIS) that was developed through an international collaboration between NASA/NRL, the UK, Norway, and Japan, was launched on the Japanese *Hinode* spacecraft, also in 2006. EIS obtains monochromatic spectral images of the solar corona at unprecedented spatial and spectral resolution, allowing the physical properties of the corona to be measured as never before. Third, NASA's Gamma Ray Large Area Space Telescope (GLAST) Observatory, which launched in 2008 and was rechristened *Fermi* at launch, is a tremendous astrophysical mission that is opening up the gamma ray sky. NRL SSD has played leading roles in the development of GLAST for many years, from providing early concepts for the Large Area Telescope (LAT), through significant LAT calorimeter hardware development, NRL on-site environmental testing of the entire spacecraft, and current *Fermi* mission science research. The SSD high energy space environment research program also has led to the development of a range of effective gamma ray imaging systems for the detection of radiation/ nuclear weapons of mass destruction. During this decade, the Remote Atmospheric and Ionospheric Detection System (RAIDS) was installed on the International Space Station to remotely sense the Earth’s thermosphere and ionosphere by scanning and imaging the atmospheric limb, and SSD developed and flew aboard the DoD Space Test Program (STP) Satellite-1 (STPSat-1) the Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER), which is a new type of compact and rugged high-resolution ultraviolet spectrometer that remotely sensed polar mesospheric clouds for more than two years of successful on-orbit operations. Further significant space experiments were the Tiny Ionospheric Photometer (TIP) experiment that launched on the Formosat-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) satellite constellation and produced global maps of the nightside ionosphere; and, twin SSD spherical spacecraft, Castor and Pollux of the NRL Atmospheric Neutral Density Experiment (ANDE), were deployed into orbit by the DoD STP from the Space Shuttle Endeavour.

PREFACE

We offer these summaries of Naval Research Laboratory (NRL) Space Science Division (SSD) research achievements to provide a technical overview of NRL space science accomplishments from the beginning of the Division in 1952 through the first decade of the 21st century.

These summaries are presented in five Volumes:

Volume 1. NRL SSD Research Achievements: 1960-1970
Volume 2. NRL SSD Research Achievements: 1970-1980
Volume 3. NRL SSD Research Achievements: 1980-1990
Volume 4. NRL SSD Research Achievements: 1990-2000
Volume 5. NRL SSD Research Achievements: 2000-2010

The importance of space science basic research in support of naval needs was robustly championed by Homer Newell, the Division's second Superintendent, who noted to the US Congress in 1957, "A strong basic research program is essential to continuing vitality of applied R&D in missiles or any other military or peacetime applications. New facts, new ideas, new techniques, new materials, new instruments, all come from the basic research effort..." As the dozens of summaries in these five Volumes tremendously attest, extraordinary ranges of research and results have been achieved.

To document significant SSD historical accomplishments, Drs. George Doschek and Jill Dahlburg requested current and former SSD researchers to contribute technical achievement summaries to these Volumes on the basis of their personal memories about the scientific activities in which they were involved. The contributions received were then loosely organized by decade into these five featured Volumes, after being edited for clarity by George Doschek, Tanisha Lucas, and Jill Dahlburg.

George Doschek would like to express his gratitude to all the researchers who have contributed to these summaries, and particularly to those with whom he has personally worked. The SSD has and is currently continuing to provide substantive and significant contributions to the developments of experimental space science since its origins after World War II, and it has been a privilege to be part of this effort. These Volumes convey stories about curiosity, hopes, and aspirations of scientists fascinated by exploration of the Universe with instrumentation placed beyond the Earth's atmosphere.

Tanisha Lucas wishes to acknowledge that she has benefited from the advice, assistance, and all of the contributions that our researchers put into these documents. She wishes to express her gratitude to the NRL SSD researchers for their remarkable scientific contributions, her appreciation for the advice on content and organization for this book provided by Dr. Jill Dahlburg, and her many thanks to Dr. George Doschek for closely working with her in compiling and arranging these Volumes.

Jill Dahlburg acknowledges with pleasure and gratitude the request from Dr. John Montgomery, NRL Director of Research, that these Volumes be developed. They present a unique account of exceptional contributions from the NRL SSD broad-spectrum research, development and experimentation program to study the atmospheres of the Sun and the Earth, the physics and properties of high-energy space environments, and solar activity and its effects on the Earth's atmosphere, and to transition these capabilities to operational use.

Finally, George, Tanisha and Jill would together like to thank Ms. Kathryn Grouss who worked with us to prepare these Volumes during 2014, for her exceptional cooperation, professionalism, assistance and advice, and to Dr. Angelina Callahan, NRL Associate Historian, for her many beneficial insights and suggestions, and her unswerving encouragement.

George Doschek, *NRL SSD Historian*
Tanisha Lucas, *NRL SSD Research Achievements Managing Editor*
Jill Dahlburg, *NRL SSD Superintendent*

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Table of Contents

Overview of the NRL Space Science Division 2000s Decade

At the US Naval Research Laboratory (NRL), the story of space research formally began in 1952, with the creation of the NRL Atmospheres and Astrophysics (A&A) Division under the direction of Dr. John Hagen, and a Division charter to perform research and development in the field of space science. The Division's second Superintendent, Homer Newell (1956-1958), continued A&A's seminal space research both at NRL and then later at the National Aeronautics and Space Administration (NASA). Following Dr. Newell's departure to NASA in 1958, Herbert Friedman assumed leadership of NRL space science as the third A&A Division Superintendent (1958-1982). Dr. Friedman oversaw the renaming of the Division from A&A to Space Science, in 1968, and in 1982 he transitioned the Division to the leadership of Dr. Herbert Gursky, who served as SSD's fourth Superintendent from 1982-2006. Jill Dahlburg, the fifth and current SSD Superintendent, was appointed to the position in 2007 following her service as Acting SSD Superintendent from May 2006. The scope of the NRL Space Science Division encompasses theoretical, experimental and numerical research of geophysics science and technology, solar and heliospheric physics, and the high-energy space environment, and the conception, design, fabrication, integration, test, operation and experimentation with forefront space instrumentation, for the purpose of enabling Navy/ Marine Corps and wider DoD robust access to space assets.

The 2000's were banner years for the Naval Research Laboratory (NRL) Space Science Division (SSD), with participation in several major space experiments and associated scientific research.

High energy space environment research was tremendously furthered in the 2000's with *Fermi*, a major world-class gamma ray mission that is revealing much about the high energy Universe. *Fermi's* Large Area Telescope (LAT) is a collaborative effort with major SSD conceptual and hardware contributions and significant scientific research products. In addition, during the fall of 2007 NRL hosted the complete *Fermi* spacecraft on site for its final environmental tests, thereby preserving *Fermi's* June 2008 launch date. *Fermi*, which is opening up the gamma-ray sky as described in Essay 2000's.1, was made possible through collaboration between NASA and the Department of Energy (DOE). The SSD high energy space environment research program also led to the development of a breadth of effective gamma ray imaging systems for the detection of radiation/ nuclear weapons of mass destruction. Among these are gamma ray spectroscopic imaging systems (Mobile Imaging and Spectroscopic Threat Identification, MISTI and SuperMISTI)) that can detect radiation/ nuclear weapons of mass destruction, which are overviewed in Essay 2000's.2.

In the 2000's solar and heliophysics research, the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument suite of coronagraphs and extreme-ultraviolet imagers were flown on the twin NASA Solar *TErrestrial Relations Observatory* (*STEREO*) spacecraft; see Essay 2000's.3 for the SECCHI story. The solar Extreme-ultraviolet Imaging Spectrometer (EIS), developed through an international collaboration between NASA/NRL, the UK, Norway, and Japan, was launched on the Japanese *Hinode* spacecraft. EIS obtains monochromatic spectral images of the corona at unprecedented spatial and spectral resolution allowing the physical properties of the corona, such as temperature, density, and dynamics, to be measured as never before, as described in essay 2000's.4.

In the area of geophysics science and technology, significant accomplishments included the SSD-led development of a compact and rugged high-resolution ultraviolet spectrometer, the Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER). As the primary payload on the DoD Space Test Program (STP) Satellite-1, SHIMMER measured hydroxyl in the mesosphere and detected polar mesospheric clouds; see Essay 2000's.5 for a summary. A new simulation capability to model the Earth's upper atmosphere was developed at NRL in the 2000's, the Navy Operational Global Atmospheric Prediction System-Alpha (NOGAPS-ALPHA), as described in Essay 2000's.6. This prototype model became the first to generate global meteorological predictions from the ground to the edge of space, and was validated with SHIMMER data. RAIDS (Remote Atmospheric and Ionospheric Detection System) was installed on the International Space Station and remotely sensed the Earth's thermosphere and ionosphere by scanning and imaging the atmospheric limb, as discussed in Essay 2000's.7. The Tiny Ionospheric Photometer (TIP) experiment launched on the Formosat-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) satellite constellation and produced global maps of the nightside ionosphere (Essay 2000's.8). And, as summarized in Essay 2000's.9, two small SSD spherical spacecraft, part of the NRL Atmospheric Neutral Density Experiment (ANDE), were deployed into orbit by the DoD STP from the Space Shuttle Endeavour STS-127.

2000's.1: The *Fermi* Gamma-ray Space Telescope Mission

Contributed by W. Neil Johnson

1.0 Introduction

It was not long after the launch of the *Compton Gamma Ray Observatory* (*CGRO*) in 1991 and its first observations of the gamma-ray sky that *CGRO* scientists began thinking about follow-on instrument concepts, incorporating new technologies from high energy particle physics experiments, that would greatly improve on the performance of *CGRO's* Energetic Gamma Ray Experiment Telescope (EGRET) observing at energies above 30 MeV. As described in the 80s Chapter Essay 80s.2, the EGRET instrument had produced a revolutionary change in our understanding of the Universe. In particular, breakthrough observations by EGRET of high-energy gamma-ray blazars, pulsars, unidentified sources, delayed emission from gamma-ray bursts and solar flares, and diffuse radiation from our Galaxy and beyond, had all changed our view of the high-energy Universe and raised many new questions. Early concepts for the follow-on instrument, called *Gamma-ray Large Area Space Telescope* (*GLAST*), were developed in a community-wide NASA-funded Supporting Research and Technology program in 1992 and a Mission Concept Study in 1994. NRL's Space Science Division (SSD) scientists joined in the *GLAST* Mission Concept study, which was led by Peter Michelson at Stanford University, and the SSD had lead responsibilities for the calorimeter or energy-measuring subsystem and significant roles in the data acquisition and flight computer subsystems.

From the start, *GLAST* was planned as an international experiment with characteristics of the large international collaborations supporting high-energy particle physics experiments at accelerator facilities such as Stanford Linear Accelerator Center (SLAC), FERMILAB and CERN. It was also the first collaborative experiment for the US Department of Energy (DOE) and NASA who shared management responsibilities for *GLAST* instrument. Throughout the remainder of the 1990's the concept for the *GLAST* instrument was refined and tested via prototype instrument components that were subjected to accelerator beam tests at SLAC Accelerator Center and at CERN in Europe. NRL's team led the development of the calorimeter subsystem and built the Beam Test Calorimeter for the NASA Advanced Technology Program which culminated in the demonstration of the *GLAST* design in a complete module prototype of the flight instrument in a 1999 beam test and subsequent balloon flight. By August of 1999 when NASA published the Announcement of Opportunity for the *GLAST* Mission, the instrument concept was well understood and the international team of collaborators was defined, including major instrument contributions from Japan, France, Sweden and Italy. Since NASA used the *GLAST* name for the mission, the instrument was renamed the Large Area Telescope (LAT) for the *GLAST* mission. In February 2000, the LAT team, lead by Peter Michelson at Stanford University, was selected to provide the main instrument for the *GLAST* mission. A second, smaller Gamma Ray Burst instrument, the Gamma-ray Burst Monitor (GBM), was to be provided by a team from Marshall Space Flight Center and Max Planck Institute in Germany.

2.0 The LAT Instrument

LAT is a modular instrument made from sixteen identical units, called towers, which consist of a tracking module with a calorimeter module below (See Figure 2000s.1.1). The 4x4 array of towers is covered by a charged-particle rejection system and controlled by a trigger and data flow system that configures the detector systems, collects their data and processes it for transmission to the ground.

Figure 2000s.1.1. Photo of one of the 19 calorimeter modules (16 for flight, 3 spare) during assembly in the clean room at NRL. James Lee (left, ATK, Inc.) and Mary Johnson-Rambert (NRL/SSD) are attaching the electronic circuits to the four sides of the module. Each calorimeter module weighs about 90 kg. Completed modules are seen in the background in electrostatic bags (credit: NRL).

Figure 2000s.1.1. Photo of the LAT during assembly with the charged particle detection system removed. The 4x4 array of tracker modules is visible. NRL's 16 calorimeter modules are mounted below the trackers. The ~3,000 kg instrument is ~1.7m on a side and 1m tall (credit: SLAC).

For the *GLAST* mission, SSD scientists were responsible for the Calorimeter Subsystem and supported the Trigger and Data Flow Subsystem with software design and test. SSD in collaboration with NRL's Spacecraft Engineering Department were also responsible for the environmental testing of the assembled LAT instrument. For the flight instrument, NRL and its collaborators built 19 Calorimeter modules – 16 for flight and 3 for ground testing and calibration investigations. The NRL team, under the leadership of Neil Johnson of NRL/SSD, managed the design, manufacturing, assembly and test effort. Major contributions to the Calorimeter subsystem

came from the Royal Institute of Technology in Sweden, that purchased approximately 2,000 CsI scintillation crystals, Laboratoire Leprince-Ringuet of Ecole Polytechnique in France, that provided the design and manufacture of the calorimeter mechanical structures, and the SLAC Accelerator Center, that provided custom electronic component designs. Key NRL team members were J. Eric Grove (SSD) who managed the assembly and test planning and execution, Paul Dizon (ATK, Inc.) who managed the overall mechanical design and qualification, James Ampe (Praxis, Inc.) who managed the electronics design and assembly, Nick Virmani (ATK, Inc.) who managed the quality assurance and safety team, Byron Leas (Interface Control Systems, Inc.) who provided ground test and calibration software, Patty Sandora (then in SSD) who performed incoming inspections and processing on the CsI scintillation detectors, and Mary Johnson-Rambert (SSD) who performed precision electronics and wiring assembly. Bill Raynor of NRL's Spacecraft Engineering Department (SED) of the Navy Center for Space Technology provided program management support and coordinated assembly and environmental test activities in SED's test facilities at NRL.

NRL team members Michael Lovellette (SSD) and Dan Wood (Praxis, Inc.) provided design and software support to LAT Trigger and Data Flow Subsystem. SSD's Chuck Dermer and Kent Wood, were instrumental in the organization and specification of the science plan and supporting documentation. On completion of assembly and initial testing of the LAT instrument at SLAC, the instrument was returned to NRL's Spacecraft Engineering Department for environmental testing led by Neil Johnson and Bill Raynor (see Figure 2000s.1.2). Eric Grove served as LAT Commissioner, responsible for defining and executing the functional testing of the instrument on the ground and later the performance verification and calibration on orbit. The qualified instrument was then delivered to NASA's spacecraft contractor, General Dynamics, for integration with the spacecraft in September 2006. Due to facilities conflicts at General Dynamics, NASA requested NRL's support for the mission thermal vacuum test. Consequently, the entire spacecraft was shipped to NRL in November 2007 for this critical final environmental test in the SED facilities. NRL's ability to support this test saved the *GLAST* mission several months in schedule delay and associated costs, and enabled the scheduled launch to be met.

Figure 2000s.1.2. NRL and SLAC team members supporting the Fermi LAT environmental testing stand in front of NRL's "Big Blue" thermal vacuum chamber. LAT, in the chamber, was tested for performance with the thermal and vacuum stresses of the space environment as well as simulated solar input (credit NRL).

3.0 Science with *Fermi*

With its launch in June 2008 into low Earth orbit, the name *GLAST* was changed to *Fermi*, and *Fermi* began a planned 10-year exploration of the most extreme environments in the Universe using imaging and spectroscopy of the gamma-ray signatures above 30 MeV in energy and reaching to energies far beyond anything possible to generate on Earth. *Fermi*'s large field of view and optimized viewing strategies permit it to view the entire sky every three hours and thereby provides excellent sensitivity to transient phenomena on time scales from milliseconds to days. *Fermi*'s science objectives include:

- a search for signs of new laws of physics and the composition of the mysterious Dark Matter,
- an understanding of the processes by which black holes accelerate large jets of material to speeds approaching the speed of light,
- an exploration of the mysteries of the powerful explosions called gamma-ray bursts, and
- an enhanced understanding of long-standing questions across a broad range of topics, including pulsars, solar flares and the origin of cosmic rays.

In its first years of operation, *Fermi* observations have more than tripled the number of known classes of high-energy gamma-ray emitters. The Second *Fermi* Source Catalog, from two years of data, identified over 1,800 gamma ray sources (see Figure 2000s.1.4). The population of gamma-ray pulsars has grown from 6 to >100, opening new windows on millisecond and radio-quiet pulsars and clarifying the nature of the gamma-ray emission. Over 1,000 gamma-ray emitting Active Galactic Nuclei (AGN) are now known, revealing a more unified picture of gamma-ray emission from galaxies, along with new types of objects seen in gamma-rays. Supernova remnant (SNR) studies and analyses of the diffuse gamma-ray emission are providing new insights on the origin of cosmic rays. Some highlights of the first four years of operation are given below:

- ***Fermi* 2FGL Catalog:** The 2nd *Fermi* LAT source catalog, covering 2 years of mission observations, includes an inventory of 1,873 gamma-ray emitting objects. Of these, 57% are blazars, 6% are pulsars, 4% are supernova remnants, and 31% are unassociated with objects detected at other wavelengths. Searches for possible counterparts of these unknown sources are on-going, with the hope of identifying new classes of astrophysical objects capable of energetic emission. The growing number of detected and imaged supernova remnants strongly suggests that these objects are the source of galactic cosmic rays and are shining in gamma rays generated by the collision of accelerated cosmic ray protons with surrounding gas clouds.

- ***Fermi* discovers 100 pulsars:** The LAT instrument has dramatically changed the understanding of gamma-ray pulsars. Prior to launch, there were 6 known gamma-ray emitting pulsars. *Fermi* announced in 2012 the detection of its 100th pulsar. They are approximately equally divided into young radio selected pulsars, young gamma ray pulsars (nearly all of which are radio quiet), and old millisecond pulsars (MSP). The radio-quiet pulsars seen by *Fermi* demonstrate that the g-ray emission beam, produced in the outer magnetosphere via curvature radiation, is much broader than the radio beam, allowing *Fermi* to make a relatively unbiased survey of core-collapse SNRs in our Galaxy and thus open a new window on stellar evolution. Through spectral characterizations, LAT has identified candidate pulsars which when studied in radio are shown to be millisecond pulsars. Thus LAT has almost doubled the known MSPs. The extremely stable rotation properties of some MSPs make them highly sought for use in radio timing arrays to detect gravitational waves.

- ***Fermi* 2LAC Catalog:** The 2nd LAT AGN Catalog (2LAC) from 2 years of mission observations identifies 1,017 gamma-ray sources at high Galactic latitudes that can be associated with AGNs identified in other wavebands. The catalog lists approximately equal numbers of Flat Spectrum Radio Quiet (FSRQ) blazars and BL Lacertae objects (BL Lac

objects), with the redshift distribution for FSRQs peaking at a z ~ 1, with the redshift distribution of BLLacs distributed at much lower redshifts (though less than 50% of BL Lacs have secure redshifts). The Clean Sample with single associations and no analysis flags includes 886 AGNs, comprising 395 BL Lac objects, 310 flat-spectrum radio quasars (FSRQs), 157 candidate blazars of unknown type (i.e., with broadband blazar characteristics but with no optical spectral measurement yet), 8 misaligned AGNs and radio galaxies, 4 narrow line Seyfert 1 (NLS1s), 10 AGNs of other types, and 2 starburst galaxies. This represents the largest catalog of Active Galactic Nuclei detected at gamma-ray energies.

- **Gamma-Ray Bursts (GRB):** Sensitive high-energy γ-ray observations of GRBs with the LAT and *Fermi*'s other instrument, the GBM, have enabled detailed studies of the temporal and spectral behavior over 7 decades energy and provided insight into the emission mechanisms of these powerful outbursts. The major discoveries from *Fermi* include: i) a delayed onset of >100 MeV prompt emission photons compared to the keV-MeV photons, by < 1s in short GRBs to several seconds in long GRBs, ii) confirmation of an additional prompt power-law spectral component hinted at by EGRET and in at least one case with an exponential cutoff, iii) temporally extended >100 MeV emission lasting minutes to hours longer than the keV- MeV prompt emission and decaying as a power law with time, iv) extremely high bulk Lorentz factors inferred from cutoffs and highest energy γ-rays via the γγ opacity considerations for LAT GRBs, v) near simultaneity GeV and MeV emissions from a short GRB led to the most stringent constraint to date on quantum gravity models that allow Lorentz Invariance Violation, and vi) the radio to γ-ray afterglows of LAT GRBs, which indicate a category of hyper-energetic bursts that challenge central engine models.

These are but a few of the results of the first four years of *Fermi* LAT observations to which NRL's science team under the leadership of NRL/SSD researchers Neil Johnson, Eric Grove, Kent Wood, Paul Ray, Chuck Dermer and Justin Finke have made significant contributions. *Fermi* has no expendable resources that would limit its life and observations through at least 2018 are expected to provide many more exciting results.

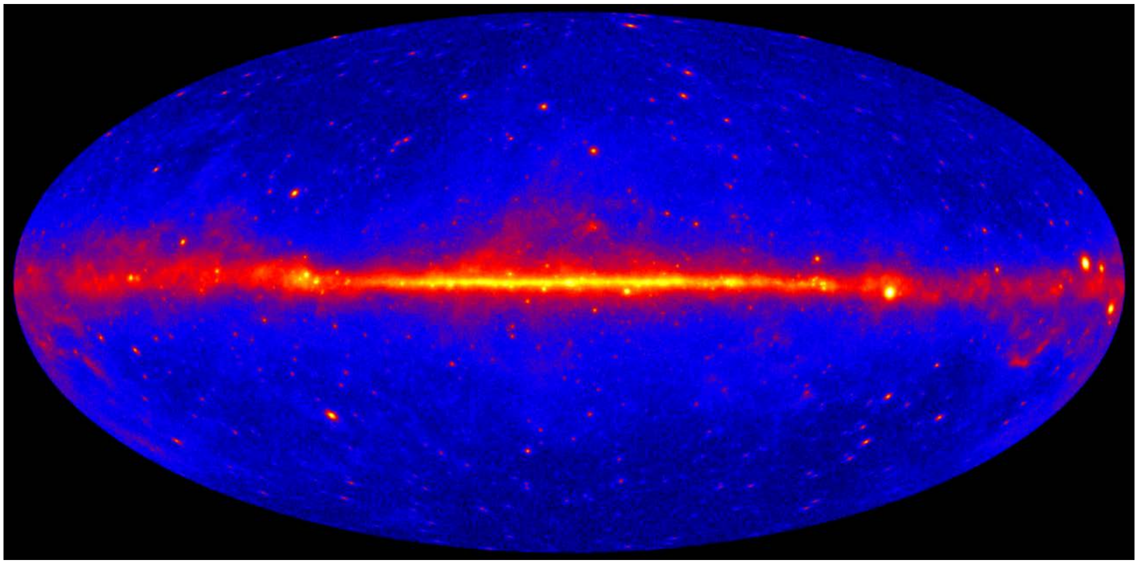

Figure 2000s.1.3. The Fermi LAT all sky false color map shown in the coordinate system of the Galaxy using the data from the first two years of the mission. The bright horizontal band is the plane of our Galaxy where cosmic rays interact with the gas and dust to create a diffuse gamma-ray emission. The 2FGL (two year) source catalog identified 1,873 point sources of gamma ray emission (credit: Fermi Team).

References: 2000s.1: The Fermi Gamma-ray Space Telescope Mission

Nolan, P. L., A. A. Abdo, et al. (2012). "*Fermi* Large Area Telescope Second Source Catalog." Astrophysical Journal Supplement Series 199(2).

Saz Parkinson, P. M., M. Dormody, et al. (2010). "Eight Gamma-ray Pulsars Discovered in Blind Frequency Searches of *Fermi* LAT Data." The Astrophysical Journal 725: 571-584.

Ransom, S. M., P. S. Ray, et al. (2011). "Three Millisecond Pulsars in *Fermi* LAT Unassociated Bright Sources." The Astrophysical Journal 727: L16.

Keith, M. J., S. Johnston, et al. (2011). "Discovery of millisecond pulsars in radio searches of southern *Fermi* Large Area Telescope sources." Monthly Notices of the Royal Astronomical Society 414(2): 1292-1300.

Ackermann, M. et al., (2011), “The Second Catalog of Active Galactic Nuclei Detected by the *Fermi* LAT”, ApJ, 743: 171.

Abdo, A. A., M. Ackermann, et al. (2010). "*Fermi* Detection of Delayed GeV Emission from the Short Gamma-Ray Burst 081024B." The Astrophysical Journal 712: 558-564.

Ackermann, M., M. Ajello, et al. (2011). "Detection of a Spectral Break in the Extra Hard Component of GRB 090926A." The Astrophysical Journal 729: 114.

2000's.2: Mobile Imaging and Spectroscopic Threat Identification (MISTI)

Contributed by Lee Mitchell, Bernard Phlips, W. Neil Johnson, Eric Wulf, and Anthony Hutcheson

1.0 Introduction

Following the events of September 11, 2001, the Secretary of Defense has made combating the proliferation of weapons of mass destruction (WMD) a science and technology priority investment [1]. The Department of Defense (DoD) seeks to counter WMDs by advancing its ability to locate, secure, monitor, tag, track, interdict, eliminate and attribute WMDs and materials. The High Energy Space Environment Branch of the Space Science Division at the Naval Research Laboratory (NRL) has extensive experience in the development of advanced space-based radiation sensors. Examples of this are the Oriented Scintillation Spectrometer Experiment (OSSE) on the *COMPTON Gamma-Ray Observatory* (*CGRO*) (see 80's Chapter Essay 80s.2) and calorimeters for the *Fermi* Large Area Telescope (see Essay 2000s.1). It was this experience that enabled SSD to develop advanced ground-based systems for homeland security applications due to the similarities of the technology and principles.

This was not the first efforts of the Space Science Division in detecting radiological/nuclear Weapons of Mass Destruction. In the late 1940's, Dr. Herbert Friedman, the Division's third superintendent, used his highly sensitive detectors to analyze debris from nuclear weapons tests that might show up in rain water collected secretly at stations in Kodiak, Alaska and Washington, D.C**.** This "Project Rain Barrel" provided the first solid evidence of the Soviet's first nuclear bomb test in August 1949, through detection and identification of the fission products [2].

2.0 The Mobile Imaging and Spectroscopic Threat Identification (MISTI) Family of Systems

In 2006 the High Energy Space Environment Branch proposed the Mobile Imaging and Spectroscopic Threat Identification (MISTI) system to counter radiological WMDs and threats in response to the Department of Homeland Security's Domestic Nuclear Detection Office's (DNDO) solicitation for the advanced technology demonstrations of Stand-Off Radiation Detection Systems (SORDS) [3]. Developed at NRL, MISTI combines a variety of commercial off-the-shelf (COTS) detectors and electronics to create one of the world's most sensitive mobile gamma-ray imaging and spectroscopic systems. MISTI was envisioned by Dr. Bernard Phlips of the Radiation Detection Section (Code 7654), who also served as the project's principal investigator. Branch head Dr. Neil Johnson served as project manager. NRL physicist and co-investigator Dr. Eric Wulf spearheaded the electronics and software integration into a functioning system. National Research Council (NRC) postdoctoral physicists Tony Hutcheson and Lee Mitchell (both now members of the SSD) aided in the development and testing of hardware and software.

References: 2000s.2: Mobile Imaging and Spectroscopic Threat Identification (MISTI)

[1] *S&T Priorities for Fiscal Years 2013-17 Planning*, Memorandum for Secretaries of the Military Departments Chairman of the Joint Chiefs of Staff Under Secretary of Defense for Acquisition, Technology and Logistics, Assistant Secretary of Defense for Research and Engineering Directors of the Defense Agencies. Apr 19, 2011.
[2] Herbert Friedman, Luther B. Lockhart and Irving H. Blifford, “Detecting The Soviet Bomb: Joe-1 In A Rain Barrel”, Physics Today, 49, 38 (1996).
[3] Advanced Technology Demonstration of Stand-Off Radiation Detection Systems, BAA07-01, Domestic Nuclear Detection Office, Dec. 18, 2006.

2000's.3: The SECCHI Instrument on the NASA *STEREO* Mission

Contributed by Russell A. Howard

1.0 The *STEREO* Mission

The *Solar Terrestrial Relations Observatory* (*STEREO*) is a NASA mission consisting of two, nearly identical spacecraft, which were launched together on Wednesday, October 25th, 2006 at 8:52 p.m. EDT on a Delta II 7925-10L rocket from Cape Canaveral Air Force Station in Florida. Both spacecraft are in orbit about the Sun at about the same distance as the Earth (93 x 10^6 miles or 1 Astronomical Unit), but one is ahead of Earth in its orbit and the other is behind. The two spacecraft are drifting from Earth at about 20 degrees each year. The drifting is achieved by having the average distance from the Sun for one spacecraft slightly less than Earth's to make it faster than Earth's motion about the Sun, and slighter further than Earth's distance for the other spacecraft to make it slower than Earth's motion.

The primary goal of the *STEREO* mission is to advance the understanding of the three-dimensional (3-D) structure of the Sun's corona, especially regarding the origin of Coronal Mass Ejections (CMEs), their evolution in the interplanetary medium, and the dynamic coupling between CMEs and the Earth environment. CMEs are the most energetic eruptions on the Sun, are the primary cause of major geomagnetic storms, and are believed to be responsible for the largest solar energetic particle events. The separation of the two spacecraft enables stereo imaging of CMEs and multipoint measurements of the solar wind, both of which have contributed to the success of the mission. Designed for two years in orbit, the mission is still operating well at the time of this essay (June, 2013). The spacecraft are currently located behind the Sun at an angle of about 140 degrees from Earth. Figure 2000s.3.1 shows one of the two spacecraft – the Behind spacecraft. The Ahead spacecraft looks very similar.

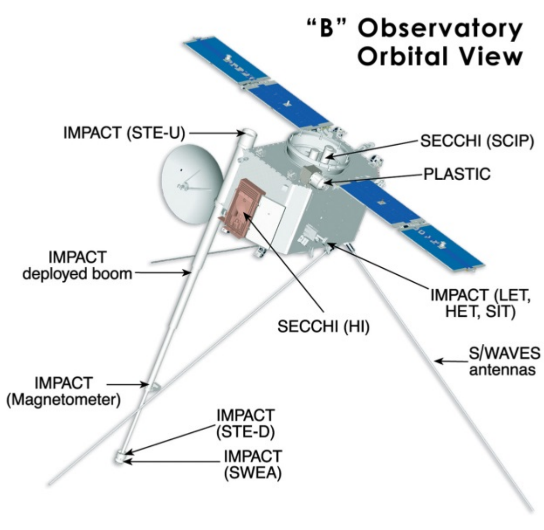

Figure 2000s.3.1 - One of the two STEREO spacecraft. The B or Behind spacecraft, shown here in its deployed configuration, was launched with the A or Ahead spacecraft on top. The two spacecraft were virtually identical with the exception of a few differences. One difference is that the attach ring shown on the top panel connected the two spacecraft together and was not necessary for the A spacecraft, saving some mass. Other differences were the locations of some of the instrument were changed to optimize their orientation to the interplanetary magnetic field (credit: NASA).

1.1 *Historical Background of STEREO*

NRL has an extensive history in the development and flight of space-borne coronagraphs (see essays in this history on the coronagraph on *OSO-7* (see *OSO* Essay 60s.2), the SOLWIND coronagraph on *P78-1*, and the LASCO coronagraph on the *Solar & Heliospheric Observatory* (*SOHO*), Essay 90s.1. The discovery of CMEs, the major culprit for adverse space weather at Earth, was made by NRL scientists analyzing data from the coronagraph on *OSO-7*. Consequently, NRL was well-poised to capitalize on any mission proposed by NASA or a foreign space agency that might involve coronagraph instrumentation.

The NASA *STEREO* mission concept was initially discussed during a conference called by the NASA Associate Administrator for Space Science, Dr. Stanley Shawhan, in 1991 [Kaiser et al, 2008]. Discussion about the mission, its objectives and mission design continued. In 1996 at a workshop to further define the concept in preparation for the Sun-Earth-Connection Roadmap, a mission concept was developed consisting of four spacecraft and was called the *Solar TErrestial RElations Observatory* (*STEREO*). In 1995, Dr. Guenter Brueckner of NRL/SSD submitted a proposal to NASA in response to a call for Medium Explorer (MIDEX) proposals, for a stereo concept using, as one eye, the LASCO instrument on the Solar and Heliospheric Observatory which was launched in December, 1995. This proposal concept was described by Dr. Dennis Socker of NRL/SSD (Socker et al, 1996, Socker, 1998). In 1996, a Science and Technology Definition Team (STDT) was established by NASA HQ to further develop the concept of the *STEREO* mission, and then in 1999, an Announcement of Opportunity to propose instruments for the *STEREO* mission was issued. NASA selected the instruments in 2000.

2.0 The *STEREO* Instruments

The two *STEREO* spacecraft payloads each contain the same instrumentation, consisting of both remote sensing and in-situ instruments. Both spacecraft look at the Sun, but one of them is rotated 180 degrees from the other. To accommodate this rotation, some of the instruments were placed to optimize their field of view with respect to the interplanetary magnetic field orientation. The remote sensing instruments include a radio telescope, *STEREO*/Waves (SWAVES), that measures the radio emission from shock waves (Type II emission) and accelerated particles (Type III emission), and a suite of five optical instruments, the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI), that observes the extreme ultraviolet Sun and the white light corona and interplanetary medium from the low corona to Earth. The in-situ instruments include two investigations. One is the In-situ Measurements of Particles and CME Transients (IMPACT) investigation which is a suite of seven instruments that samples the 3-D distribution of solar wind plasma electrons, the characteristics of the solar energetic particle (SEP) ions and electrons, and the local vector magnetic field. The other in-situ investigation is the Plasma and Suprathermal Ion Composition (PLASTIC) instrument which samples the solar wind and suprathermal particles, providing measurements of kinetic properties and composition.

NRL/SSD's Dr. Russell A. Howard is the Principal Investigator for the SECCHI investigation, which includes an international consortium. Other key members of the SECCHI development from NRL Space Science Division are J. Daniel Moses, Angelos Vourlidas, Dennis Socker, Simon Plunkett, Dennis Wang, Michael Carter, Nathan Rich, Lynn Simpson, Benjamin Au and Martin Koomen. A team from the Spacecraft Technology Center led by Amy Hurley, with Robert Skalitzky, developed the electronics system design and then built and fabricated the electronics system. The NRL/SSD provided the overall project management, the design and development of one of the white light coronagraphs, the flight and ground software, integration of all five of the SECCHI telescopes for the two spacecraft, and flight operations and data processing of the raw telemetry data. In addition, NRL provided the CCD detectors for all the telescopes. Two of the

telescopes, the extreme ultraviolet imager and the externally occulted coronagraph, were partially funded by the DoD Space Test Program as part of a program to develop the concept of a "Coronal Mass Ejection Warning System" or CMEWS. That program grew out of the success of those two instruments on *SOHO*/LASCO in identifying CMEs that would be impacting Earth.

3.0 The SECCHI Instrument

The SECCHI instrument consisted of five telescopes – one ultraviolet and 4 visible light telescopes that imaged the inner heliosphere from the solar disk out to the Earth and beyond (Howard et al., 2008). Each telescope imaged a different region as in a series of nested telescopes. All of the telescopes, several of which were unique, worked extremely well and continue to do so.

3.1 *EUVI*

The ultraviolet telescope (EUVI) was built by the Lockheed Martin Solar and Astrophysics Laboratory in Palo Alto, CA. It is a Ritchey-Chrétien design, based on the Extreme-ultraviolet Imaging Telescope (EIT) instrument on *SOHO*, and creates images of the Sun in four ultraviolet wavelength bands centered on the emission of He II at 30.4 nm, Fe X, Fe IX 17.1 nm, Fe XII 19.5 nm and Fe XV 28.4 nm. The mirrors were figured, polished and coated with a multilayer stack at the Institut d'Optique in Orsay, France. Each quadrant of the primary and secondary mirrors received a different multilayer stack, which determined the passband. These different passbands correspond roughly to emission of plasma in four temperature regimes approximately at 0.08, 0.8, 1.6 and 2.2 M K. The outer limit of the field of view is 1.7 R_{sun}.

3.2 *COR1*

The inner white light coronagraph (COR1) was built by the NASA Goddard Space Flight Center in Greenbelt, MD. It images the faint emission produced by the scattering of sunlight by the electrons in the corona. The telescope design is an adaptation of ground based internally occulted Lyot coronagraphs. The field of view begins at 1.4 R_{sun} and extends to 4 R_{sun}. It was the first refractive coronagraph design ever flown in space. The LASCO/C1 design, described in the 1990's chapter, was a reflective (mirror) design.

3.3 *COR2*

The outer white light coronagraph (COR2) was built by the Space Science Division, Naval Research Laboratory in Washington, DC. It also images the faint emission from the Thomson scattering by coronal electrons. The telescope is an adaptation of the LASCO/C2 and C3 externally-occulted Lyot coronagraphs. The field of view overlaps the COR1, beginning at 2 R_{sun} and extending to 15 R_{sun}.

3.4 *HI1 and HI2*

The two heliospheric imagers were built by the University of Birmingham in the UK, with the optics designed by the Centre Spatiale de Liege, in Liege Belgium. The design concept was originally developed by Dennis Socker. The HI's also measure the photospheric light scattered by the electrons in the solar wind, but in this region the dominant signal is generated by scattering of sunlight from interplanetary dust particles as well as stars and other galactic sources. The fields of view of HI1 and HI2 are 20^0 and 70^0, respectively, beginning at 4^0 and 18.7^0, respectively. These two telescopes encompass the region from 15 R_{sun} to Earth.

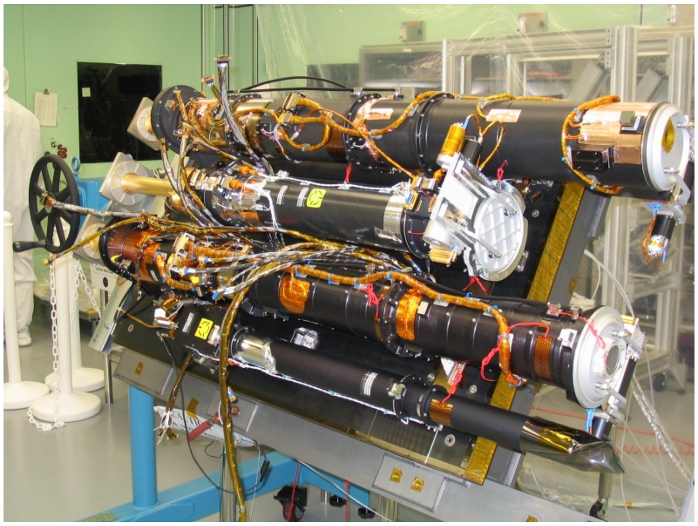

Figure 2000s.3.2 - The Sun Centered Instrument Package (SCIP) component of SECCHI. The EUVI, COR1 and COR2 needed to be pointed at the center of the Sun and were mounted onto a stable platform along with a Guide Telescope (GT). The GT provided a pointing error signal to the spacecraft and a high cadence signal to the EUVI mirror mechanism to enable image motion compensation. This view is looking toward the telescope apertures, which are covered by their doors. The telescope tubes are the dark cylindrical tubes. The gold colored harnesses supply power to the various mechanisms and heaters and receive status and temperature signals. At the rear of each of the scientific telescope is a panel to radiate heat away from the CCD detectors to achieve temperatures on the order of -70C. Dummy radiator panels are shown in this picture. This whole assembly was encased in multi-layer insulation to keep the instrument temperatures at about 20C. It was located in the center of the spacecraft, and the CCD radiators to the rear (credit: NASA/NRL).

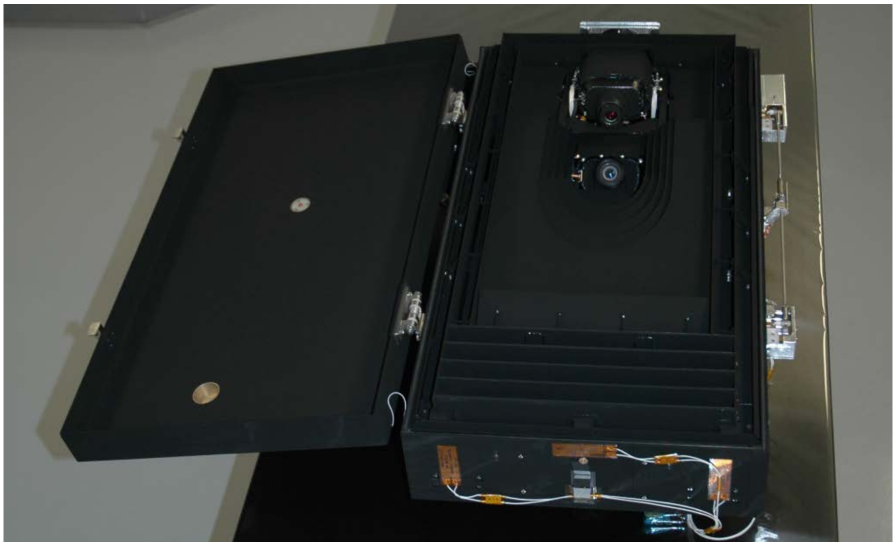

Figure 2000s.3.3 - The Heliospheric Imager (HI) package of the SECCHI instrument. The HI was mounted on the side of the spacecraft and looks along the Sun-Earth line. Two telescopes are at the far end of the package, which has occulters and baffles to block unwanted stray light from entering the apertures. Everything is coated with black paint or some other low-scattering material to reduce the light from the Sun by more than a factor of 10^{-10}. The door which covered the entire box is shown in the deployed configuration. It protected the instrument from dust during the ground operations and launch (credit: NASA/NRL).

4.0 Science Results

- SECCHI has shown that CMEs are 3-D magnetic fluxropes. The association of the fluxrope to CMEs was initially made with two CMEs observed by LASCO, but SECCHI has made the question now: Is the magnetic flux rope the only structure of a CME?
- SECCHI has shown that EIT waves are the shocks driven by the expanding CME. The EIT wave was initially observed by OSO-7 in the early 1970s, but the physical mechanism was debated, ranging from thermal waves to MHD waves generated by a flare, until now.
- SECCHI has measured CME rotation in 3-D in both the low corona and the inner heliosphere. Theoretical modeling predicted that CMEs could undergo rotation in their propagation, but rotation had never been observed in previous coronagraphs. This has implications for predicting the magnetic field direction at Earth.
- SECCHI imaged Corotating Interaction Regions (CIRs) for the first time and imaged their arrival at Earth.
- SECCHI followed the complete lifetime of active regions (implications for coronal heating).
- SECCHI discovered 'Stealth' CMEs. A class of CMEs has been observed that has no photospheric or chromospheric counterpart. This has implications for predicting a quiet geomagnetic field using only flare and EUV monitors.
- SECCHI has improved the accuracy of arrival times at earth for CMEs from ± 12 hours to ~+/- 4 hours and for CIR impact from nonexistent to ± 2 hrs.
- SECCHI has imaged the impact of a CME on a comet tail. Comet tails behave like the terrestrial magnetosphere. A tail disruption occurs not when the high pressure (due to the enhanced CME density) crosses the comet but when the high magnetic field from the flux rope crosses.
- SECCHI demonstrated that super-elastic collisions between two CMEs are possible.
- SECCHI has discovered 248 new variable stars and 1 tentative detection of an exoplanet.
- SECCHI has measured the first 3-D velocities, directions, sizes of coronal eruptive structures.
- SECCHI has produced the first 360 degree maps of a stellar atmosphere.
- SECCHI has discovered long-range couplings among eruptive events (flares and CMEs).

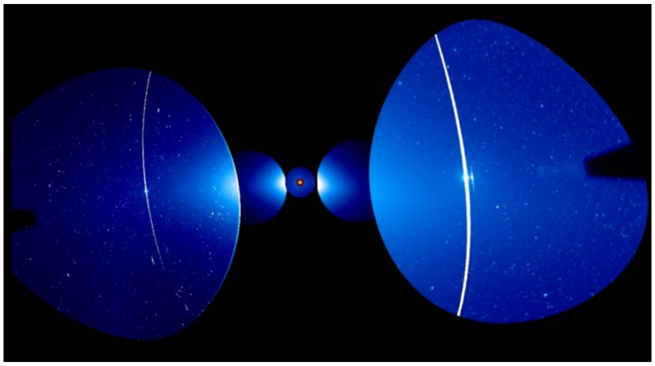

Figure 2000s.3.4 - An unprecedented view of the inner heliosphere. If you were in space and stretched your hands out to your sides, this is the view that you would have from one hand to the other. Starting from the left, the first image is the HI-2A, then HI-1A, then COR2, COR1 and EUVI, then HI-1B, HI-2B. The traditional view that we have had of the Sun and its corona is the small circular image of COR2, COR1 and EUVI. The images have been corrected for the image distortion, which makes the lines curved. Earth is imaged on the right and our moon is shown just to the right. Venus is the planet in the left HI-2A image. The planets saturate the detector, causing the vertical stripes up and down the image. The bright region at the sunward side of the HI images is the zodiacal light, created by sunlight scattering off the dust particles in space (credit: NASA/NRL).

5.0 Impact of the SSD Science Results

Since the *SOHO*/LASCO era, we have put the data onto the web as soon as possible after collection by our ground stations. This is in line with the NASA data policy. This has been received very favorably by the scientific community - there are over 5,000 publications utilizing the SECCHI data. The NRL is known for its ability to conceive and build state-of-the art coronagraphic instrumentation and then distribute the calibrated data to the community. As can be seen from the list of science results, the SECCHI instrument suite has been extraordinarily successful in settling some long standing questions in solar physics but also in achieving a number of "firsts".

(GAD editor's note: Russell Howard won the NASA Exceptional Scientific Achievement Award in 2008 for his leadership in making the *STEREO* mission a spectacular success.)

6.0 Relevance to Navy/DoD

The Sun is a major source of particles and magnetic fields impacting the Earth's environment. It is only recently that this has become a system problem in defining the near-space environment that the Navy and the DoD must operate in. SECCHI is providing key insights in how to monitor the flux of solar radiation and particles, and in how the propagation occurs from the Sun to Earth.

References: 2000s.3: The SECCHI Instrument on the NASA STEREO Mission

Howard, R. A., et al. (2008), Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI), Space Science Reviews, 136, 67-115.

Kaiser, M. L., T. A. Kucera, J. M. Davila, O. C. St. Cyr, M. Guhathakurta, and E. Christian (2008), The *STEREO* Mission: An Introduction, Space Science Reviews, 136, 5-16.

Nieves-Chinchilla, T., R. Colaninno, A. Vourlidas, A. Szabo, R. P. Lepping, S. A. Boardsen, B. J. Anderson, and H. Korth (2012), Remote and in situ observations of an unusual Earth-directed coronal mass ejection from multiple viewpoints, Journal of Geophysical Research (Space Physics), 117, 6106.

Socker, D. G., et al. (1996), *STEREO*: a solar terrestrial event observer mission concept, Proc. SPIE, 2804(Missions to the Sun), 50-61.

Socker, D. G. (1998), Stereographic image potential of a *STEREO* mission, Proc. SPIE, 3442, 44-52.

Socker, D. G., R. A. Howard, C. M. Korendyke, G. M. Simnett, and D. F. Webb (2000), NASA *Solar Terrestrial Relations Observatory* (*STEREO*) mission heliospheric imager, Proc. SPIE, 4139 (Instrumentation for UV/EUV Astronomy and Solar Missions), 284-293.

Thernisien, A., A. Vourlidas, and R. A. Howard (2009), Forward Modeling of Coronal Mass Ejections Using *STEREO*/SECCHI Data, Solar Physics, 256, 111-130.

2000's.4: The Extreme-ultraviolet Imaging Spectrometer (EIS) on the Japanese *Hinode* (Solar-B) Spacecraft

Contributed by George A. Doschek

1.0 Background

After the outstanding success of *Yohkoh* (Solar-A) the Japanese decided to embark on a much more ambitious solar physics mission, sponsored by the now Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency (ISAS/JAXA). The mission was called Solar-B until launch and then renamed *Hinode* (Sunrise, in English). The Japanese had agreed among themselves to fly a 50 cm white (visible) light telescope to observe the solar photosphere and part of the chromosphere at very high spatial resolution (diffraction limited), comparable to the resolution of ground-based solar telescopes. Although the effects of atmospheric blurring of images (seeing) for ground-based observations can be greatly mitigated with adaptive optics, high quality images can only be obtained for short times and over small fields of view. In contrast, a space-based white light telescope can observe a large field-of-view at uniformly high spatial resolution over long time periods. Such a telescope had never before been flown in orbit. The white-light Sun was the last large solar system object to be explored at high spatial resolution from space. In addition, the white light telescope was to feed a complex focal plane package allowing filtergram imaging and containing a vector magnetograph. Measuring longitudinal and tangential components of the photospheric magnetic field is important for analyzing many solar problems.

The Japanese solar physics community also wanted to fly a high spatial resolution X-ray telescope with whole-Sun viewing, large dynamic range, and good time resolution. A debate ensued for several years as to whether the telescope should be a grazing incidence telescope, or a normal incidence extreme-ultraviolet (EUV) telescope using multilayer coated optics. Temperature coverage, spatial and time resolutions, and other factors were calculated for each type of telescope, and eventually the grazing incidence telescope was chosen.

The third instrument grew out of the *Yohkoh* Bragg Crystal Spectrometer (BCS) collaboration and the Japanese science goals. Dr. George Doschek of NRL/SSD wrote to Dr. Tetsuya Watanabe at the National Astronomical Observatory of Japan (NAOJ) in June 1992 suggesting an extreme-ultraviolet imaging spectrometer along the lines of the S082A slitless spectrograph on *Skylab*; see 70s Chapter Essay 70s.2. In the NRL suggestion, a telescope would image selected small regions of the Sun on the slit, thus eliminating the overlapping images in the *Skylab* instrument. Doschek and his colleague, Dr. Uri Feldman, in NRL/SSD had long advocated such an instrument. Dr. Watanabe was enthusiastic and had also conceived of such an instrument for the next Japanese mission. In addition, United Kingdom (UK) scientists at University College London-Mullard Space Science Laboratory (UCL-MSSL) and at other UK institutions were enthusiastic and had been planning similar instrumentation. UK scientists began working on designing their own version of an EUV spectrometer. The BCS collaboration had been very successful; however, the overall Japanese community had to be convinced of the importance of such an instrument. Accordingly, Doschek, Feldman, Drs. John Seely and Charles Brown in NRL/SSD designed several spectrometers and presented the designs to the Japanese for their consideration. Dr. Watanabe and his colleague, Dr. Hirohisa Hara, independently designed an imaging spectrometer. Calculations for the NRL spectrometer designs were carried out by Seely and Brown. In addition, UK scientists at MSSL (Professor Len Culhane and Dr. Louise Harra) worked hard to convince the Japanese of the importance of EUV spectroscopy.

An EUV imaging spectrometer can make good use of multilayer coated mirrors and a multilayer coated grating. John Seely had become an expert on the design and use of multilayer optics. He had successfully coated gratings and shown that their spectral resolution was not degraded by the coatings, and his multilayer mirror telescope images of laser-produced plasma targets were a research highlight that appeared on the cover of Applied Optics. Thus, NRL appeared to be in a good position to continue its Japanese collaboration with the much more advanced EUV imaging spectrometer. In the meantime, Dr. Joseph Davila at Goddard Space Flight Center (GSFC) successfully flew a rocket spectrometer with a multilayer coated grating and Joseph Davila later became part of the NRL effort. Thus, eventually the contributions from all the international parties involved convinced the Japanese community to accept an EUV spectrometer as a baseline Solar-B instrument.

The projected cost of the EUV imaging spectrometer was much more than the BCS instrument and thus NRL funds would be completely inadequate to fund the project. For NRL to be involved, it was necessary for NASA to continue its Japan Solar-A collaboration with Solar-B and include at least partial funding for an EUV imaging spectrometer. NASA agreed to participate with the Japanese in Solar-B and formed a Science Definition Team that had SSD's Dr. Spiro Antiochos as chair with both Doschek and SSD's Dr. Ken Dere as members, along with many other scientists. The result was a report that reflected the Japanese science goals made with possible US and UK collaborators. At about the same time, UCL-MSSL submitted a successful proposal to their funding agency Particle Physics and Astronomy Research Council (PPARC) to build the EUV imaging spectrometer for Solar-B, with support from the US. UCL-MSSL was the lead institution in building the instrument, with overall oversight of the entire project in Japan (NAOJ, ISAS/JAXA).

NASA issued an Announcement of Opportunity (AO) for Solar-B that included a provision for submitting proposals to supply hardware, etc. for the UK instrument. In addition, the NASA AO solicited proposals for the white light focal plane package and for most of the X-ray telescope (part of the X-ray camera was to be built by the Japanese). NRL submitted a successful proposal, i.e., the EIS instrument, with Doschek as the US Principal Investigator for the US/UK/Japan partnership in building the EUV spectrometer. Davila from GSFC was a Co-I on the instrument and GSFC delivered some of the hardware for the instrument. Ultimately, the University of Oslo in Norway joined the collaboration and supplied the quick look and ground-support software to the UK.

The leadership arrangement for the EIS spectrometer was similar to that of BCS but also involved NASA. Prof. Len Culhane at UCL-MSSL was the Principal Investigator of the instrument, with Tetsuya Watanabe as the Japanese Principal Investigator. The UK group also included the Rutherford Appleton Laboratory (RAL) and the University of Birmingham, who were both given significant hardware roles in building the spectrometer. The UK funding agency PPARC had a formal agreement with NASA to supply science, hardware, and operational support for the spectrometer.

The design development of the EIS spectrometer was somewhat bizarre and certainly unique. The Japanese designed an instrument which had very high spectral resolution (a few km/s Doppler precision for bright lines) but modest spatial resolution (~6"). At NRL Doschek and his colleagues brought SSD's Dr. Clarence Korendyke into the program due to his extensive knowledge of EUV spectrometers gained through the High Resolution Telescope and Spectrograph (HRTS) sounding rocket program; see 90s Chapter Essay 90s.4. Korendyke wanted to fly a three reflection optical system consisting of a Cassegrain telescope which imaged segments of the Sun on the spectrometer entrance slit and a reflection grating. Such a system had the advantage of being entirely on-axis, i.e., no astigmatism, small enough for the instrument structure to be fabricated out of aluminum in spite of its significant coefficient of thermal expansion, and small enough to be enclosed in a vacuum shell to protect it from contamination. It also had the high spectral resolution of the Japanese design and in addition had high spatial resolution (~1" pixels). In contrast the Japanese

instrument (and also the UK instrument proposed to PPARC) was a two-reflection off-axis system that would benefit greatly from a composite fiber structure to ensure thermal stability because of its size. However, the NRL three-optic system was only 25% as efficient as the Japanese/UK designs (the maximum reflectivity of the EUV multilayer coatings is about 25%) and the NRL wavelength ranges would be narrower than the Japanese/UK wavelength ranges. Neither the Japanese or UCL-MSSL liked the three-optic system very much, but NRL went ahead and proposed it to NASA. The original NRL proposal also included two CCDs positioned at the spectrometer slit plane to capture multilayer telescope context images for the spectrometer. These were the responsibility of SSD's Dr. Dan Moses. NRL's proposal was accepted without the context CCDs and there followed a kick-off meeting in Japan for Solar-B. At this meeting an all-day scientific discussion took place concerning whether or not to fly a two-optic or three-optic system. At the end of the day a high-level meeting was called including the Japanese and US Solar-B program managers, Dr. Takeo Kosugi and Mr. Larry Hill, Doschek, Dr. William Wagner, the NASA HQ solar physics discipline chief, and Culhane. A vote was taken, and the two-optic system was chosen.

However, after returning to NRL, Dr. Roger Thomas at GSFC learned of the outcome from Clarence Korendyke and they began investigating the two reflection system in great detail. Thomas had written a ray tracing program that could rapidly investigate many systems, a program not available in SSD. Thomas found a way to optimize the Japanese/UK designs so that the high spectral resolution was preserved but the spatial resolution was improved to 1" pixels. This optimized design was finally selected for flight on Solar-B.

2.0 The Solar-B Spacecraft

Solar-B was launched on 23 September 2006 (Japan time) from Japan's Uchinoura Space Center not far from Kagoshima. The orbit is a circular, Sun-synchronous polar orbit of about 680 km altitude, 98.1 degree inclination, and 98 minute period. With this orbit, the Sun is observed continuously for about nine months each year. The other three months contain interruptions due to eclipses by the Earth. These are not severe enough to disrupt observations, although they affect the performances of the instruments which are accounted for in data reduction. The spacecraft (Figure 2000s.4.1) has dimensions of about 4m x 1.6m x 1.6m with two solar panels (4.3m x 1.1m each) and weighs about 900kg. As mentioned, *Hinode* has three instruments: a white light Solar Optical Telescope (SOT), the EIS, and an X-ray Telescope (XRT). The entire mission is described by Kosugi et al. (2007).

Figure 2000s.4.1 – The Hinode (Solar-B) spacecraft. The EIS spectrometer is shown at the top. The SOT is the white light Solar Optical Telescope, and the XRT is the X-ray Telescope (credit: ISAS/JAXA).

3.0 The EIS and NRL Contributions

The EIS instrument observes two EUV wavebands: 170 – 210 Å and 250 – 290 Å. The surfaces of the 15cm diameter primary mirror and 3cm diameter 4200 line/mm toroidal laminar grating are divided into two halves and each half is coated with a Mo/Si multi-layer optimized for one of the wavebands. The primary mirror has coarse and fine movements for positioning different regions of the Sun onto the interchangeable spectrometer entrance aperture: a 1" wide slit, a 2" wide slit, a 40" wide slot, or a 266" wide slot. Two very thin aluminum filters, one in the telescope and one in the spectrometer block visible light and heat. The grating diffracts radiation onto two back-thinned e2v CCDs, 2048 x 1024 pixels; each pixel being 13.5µm square. The spatial resolution is 2" (1" pixels) and the spectral dispersion is 0.0223 Å per pixel. This corresponds to a measurement capability of 2-3 km/s Doppler velocities on the Sun when count rates are relatively high. The peak effective areas for the two wavebands are 0.30 cm^2 and 0.11 cm^2. The full CCDs can be read out or selected windows of variable size can be read out. In the windowed mode, a maximum of 25 lines can be observed in a single study. One of the narrow slits can be positioned on a solar region and the region can be tracked in a Sit&Stare mode observation. Alternatively, an entire active region can be rastered by stepping the slit east/west in small increments (typically 1"). The rastering process allows monochromatic imaging capability by integrating over a single spectral wavelength and stacking the rastered intensities. EIS is the most advanced spectrometer yet flown for observations of coronal lines emitted at temperatures greater than 1 MK.

The NRL collaboration dealt with every aspect of the EIS, i.e., science design, hardware components, integration and test, and pre-launch activities and operations after launch. NRL contributed major hardware components: an articulated multi-layer coated telescope mirror, a multi-layer coated grating with focusing capability, a thin aluminum entrance filter and mount, a post-slit thin aluminum filter and mount, a slit assembly mechanism (interchangeable slits and a shutter), and the mechanism and heater control flight electronics and associated software. The EIS end-to-end calibration was carried out at RAL with NRL participation. A simplified schematic of EIS is shown in Figure 2000s.4.2, NRL hardware components are shown in Figure 2000s.4.3, and EIS on the ground is shown in Figure 2000s.4.4. The EIS is described in detail by Culhane et al. (2007) and Korendyke et al. (2006). Calibration is described in Lang et al. (2006). The current EIS Principal Investigators as of February 2014 are Dr. Tetsuya Watanabe (Japan), Dr. Louise Harra (UK), and Dr. George Doschek (USA),

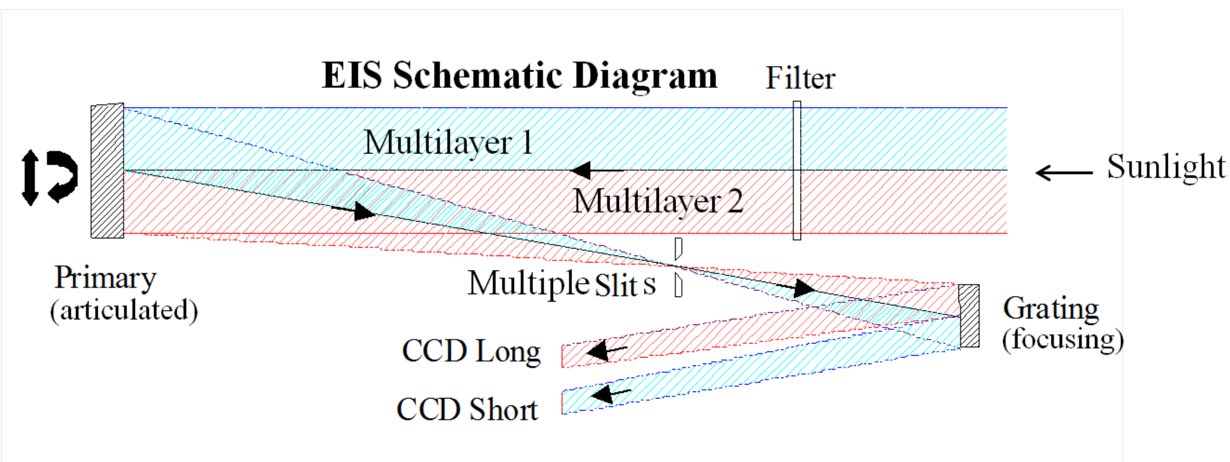

Figure 2000s.4.2 – Schematic of the EIS imaging spectrometer. See text for discussion (credit: NRL).

Figure 2000s.4.3 – The NRL EIS hardware components (credit: NRL).

Figure 2000.4.4 – EIS activities on the ground before launch. Top left - Integration with legs and shake fixture at RAL in the UK; top right - Korendyke checking focus of primary mirror in the UK; bottom - EIS (shown bagged for cleanliness) is attached to the spacecraft in Japan (credit: UCL-MSSL,RAL,JAXA).

4.0 Science Results and Impact

Hinode continues to be an extremely successful scientific mission. As of about 2013, worldwide about 700 papers in refereed journals have been published using *Hinode* data. About 290 papers using EIS data have been published in refereed journals since launch along with about 185 conference proceedings and talks. Members of the worldwide solar community can propose studies that the *Hinode* Science Working Group implements and obtains the proposed observations. Below

as of 2013 are listed some of the most important results using EIS data obtained by SSD scientists and their contractor associates (Many investigators throughout the world have done outstanding work using EIS data. However, as this is an NRL history, we stress work done by NRL scientists and contractors.):

1 - Although the EIS wavebands are rather narrow, about 500 lines are present in different solar regions but only about 55% can be identified with previously known spectral transitions (Brown et al. 2008). Thus EIS can see deeply into the solar spectrum. The identified lines belong to a total of 56 ions from 15 elements. This result has led to new investigations of the available and extensive plasma diagnostics for the identified lines in the EIS wavebands, such as electron density sensitive line ratios (e.g., Young et al. 2009).

2 - A surprising discovery made with EIS data are outflows at the edges of active regions that cover extensive areas (e.g., Doschek et al. 2008; Bryans, Young, & Doschek 2010; Ugarte-Urra & Warren 2011; Warren et al. 2011). The regions are very faint, much fainter than the active region loops, but plasma in these adjacent extended regions flows outward at speeds between 20 and 200 km/s. The spectral lines are also broader than found in the bright active region loops (Doschek et al. 2007), perhaps indicating unresolved outflow speeds. The outflows are intermittent with time scales as short as 5 minutes. Another peculiar result is the high temperatures of the outflows. Outflows are present primarily in emission lines of Fe XI – Fe XV (about 1.2 – 2 MK). Observations at lower temperatures are in contrast dominated by inflows towards the chromospheres (Warren, Ugarte-Urra, Young, & Stenborg 2011). The big issue is whether or not these outflows contribute to the slow solar wind. An example of the data is shown in Figure 2000s.4.5.

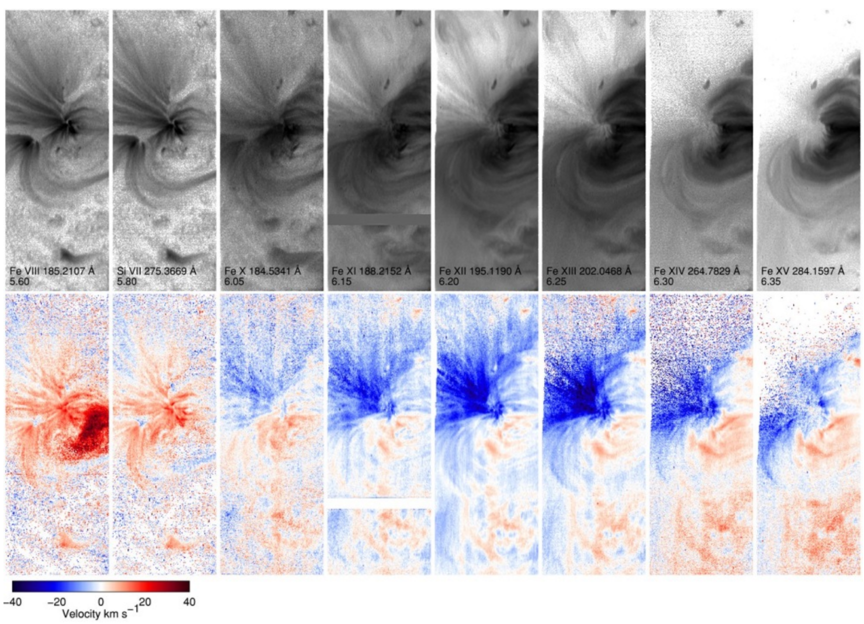

Figure 2000s.4.5 – Top: images of an active region in the spectral lines indicated along with the log of their electron temperatures of formation in ionization equilibrium. Bottom: Doppler speed images corresponding to the top intensity images. Blue indicates an outflow; red is an inflow. Note the switch from inflow to outflow between Si VII and Fe X (Figure 4 in Warren, Ugarte-Urra, Young, & Stenborg 2011; credit: reproduced by permission of the AAS).

3 - There have been many different extensive studies of active regions. A major question is how active regions are heated. A specific question is what governs the plasma heating, dynamics, and evolution in active region loops, i.e., closed magnetic flux tubes. With the plasma diagnostic capabilities of EIS, electron densities have been measured and these yield filling factors of about

10% in the denser regions of loops. This implies a spatial sub-resolution filamentary structure to the loops. Unresolved magnetic "threads" in loops are implied by the observations (Warren et al. 2008a; Warren et al. 2008b). Active region loops are of two main types: "warm" loops with temperatures of about 1.4 MK that surround a core of "hot" loops with plasma at about 2-3 MK. EIS observations show that the "hot" loops are heated quasi-steadily, while the "warm" loops are heated impulsively (Brooks & Warren 2009; Warren, Winebarger, & Brooks 2010; Warren et al. 2010). With its observation of many spectral lines over a large temperature range, EIS can obtain highly detailed emission measure distributions for the plasma in loops. The EIS emission measure distributions are the most accurate and detailed yet obtained (see Figure 2000s.4.6 for an example). The emission measure distributions of "hot" loops show that they are strongly peaked around 4 MK with a several hundred thousand degree spread. They are inconsistent with nanoflare models of loop heating that postulate that the heating is due to small random nanoflares that occur in the loop threads (Warren & Brooks 2009; Warren, Brooks, & Winebarger 2011).

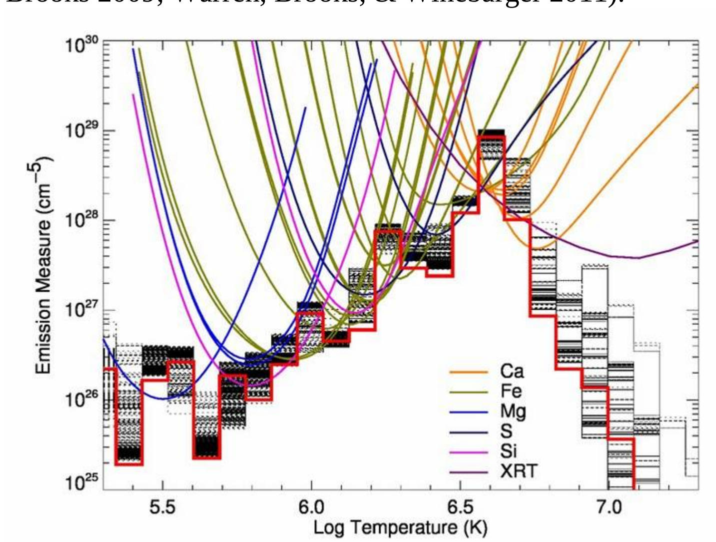

Figure 2000s.4.6 – The emission measure distribution of the hot core of an active region from Figure 4 in Warren, Brooks, & Winebarger (2011) (credit: reproduced by permission of the AAS).

4 - EIS has also detected waves in coronal loops (Mariska & Muglach 2010) at temperatures ranging from about 1.2 MK to 2-3 MK. The waves have amplitudes of 1-2 km/s and last on the order of 10 minutes. The better-observed cases are consistent with upward propagating slow magneto-acoustic waves.

5 - EIS has the capability of detecting first ionization potential (FIP) element abundance variations (Feldman et al. 2009). A measurement of abundances in the extensive outflow regions discussed above is consistent with the suggestion that these plasma outflows represent a contribution to the slow solar wind as measured near-earth (Brooks & Warren 2011).

6 - The plasma diagnostic capabilities of EIS have been used to investigate the physical conditions in bright points and even bright point jets (Dere 2009; Doschek et al. 2010).

7 - After the recent long solar minimum, EIS has begun observing many more solar flares. EIS has been able to locate footpoint regions in flares that are sources of chromospheric evaporation (Figure 2000s.4.7). Thus detailed checks of aspects of the so-called Standard Flare Model can now be attempted (Doschek, Warren, & Young 2013; Young et al. 2013).

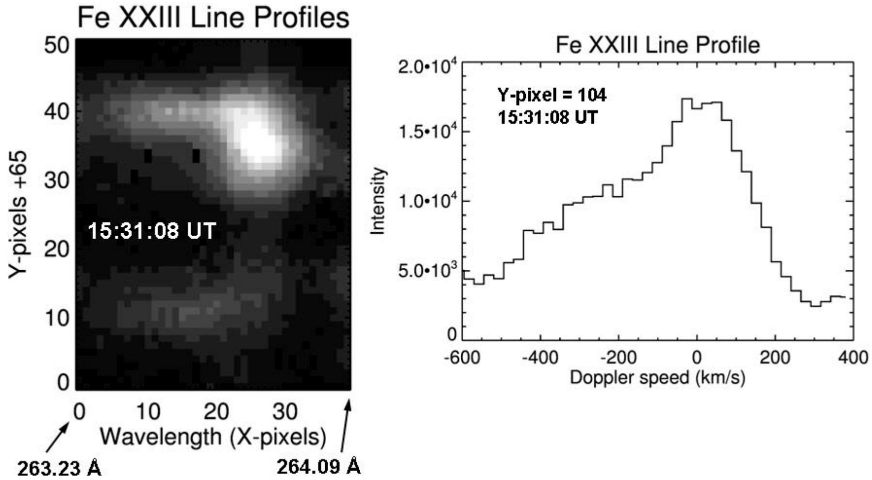

Figure 2000s.4.7 – Left: spectral image (and profiles) of a flare footpoint region in a line of Fe XXIII. In Yohkoh spectra the spatial origins of the strong blueshifts indicating evaporation could not be determined (credit: NASA/NRL).

8 - EIS images of the entire Sun have been obtained using the 40 arcsec slot. Examples are shown in Figure 2000s.4.8. The top row of figures shows two monochromatic EIS images combined into a single image, and how this single image looks quite similar to the near-simultaneously obtained image from the Extreme-ultraviolet Imaging Telescope (EIT) on *SOHO*. EIT is a broadband multi-layer filter instrument, and its response includes a broader range of temperatures than EIS monochromatic images. Thus, EIS images have better temperature resolution than filter images. The bottom left three-color EIS image shows the Sun in lines of Fe XV, Si VII, and Fe XII. Red is hot, blue is cool.

EIS observations continue as this history is being written and many more outstanding observations are anticipated.

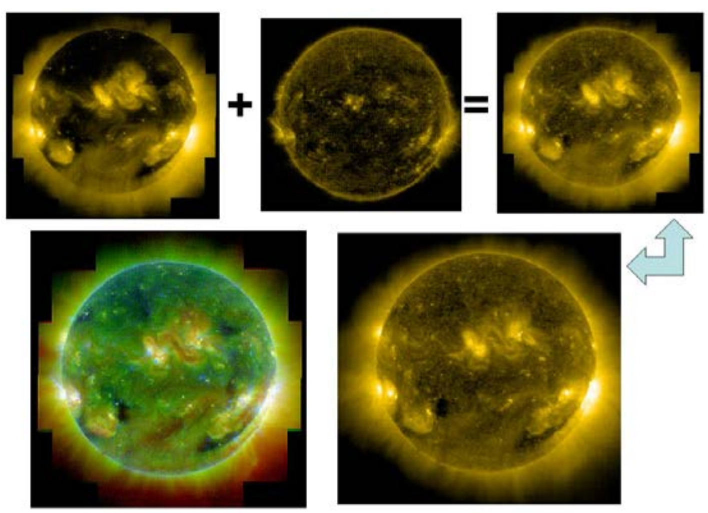

Figure 2000s.4.8 – Top left: an EIS image in a line of Fe XV (2.2 MK, 284.16 Å); top middle: an EIS image in a line Si VII (0.63 MK, 275.37 Å); top right: an EIS image combining the Fe XV and Si VII images for comparison with the bottom right EIT image, which has both EIS lines and other lines in its wavelength passband; bottom left: a three-color EIS image combining EIS images in lines of Fe XV, Si VII, and Fe XII (1.6 MK, 195.12 Å). Red is hot; blue is cool (credit: NASA/NRL).

References: 2000s.4: The Extreme-ultraviolet Imaging Spectrometer (EIS) on the Japanese *Hinode* (Solar-B) Spacecraft

Brooks, D. H., & Warren, H. P. 2009, Astrophys. J., 703, L10

Brooks, D. H., & Warren, H. P. 2011, Astrophys. J., 727, L13

Brown, C. M., Feldman, U., Seely, J. F., Korendyke, C. M., & Hara, H. 2008, Astrophys. J. Suppl., 176, 511

Bryans, P., Young, P. R., & Doschek, G. A. 2010, Astrophys. J., 715, 1012

Culhane, J. L., et al. 2007, Solar Physics, 243, 19

Dere, K. P. 2009, Astron. & Astrophys., 497, 287

Doschek, G. A., et al. 2007, Astrophys. J. (Letters), 667, L109

Doschek, G. A., Landi, E., Warren, H. P., & Harra, L. K. 2010, Astrophys. J., 710, 1806

Doschek, G. A., Warren, H. P., Mariska, J. T., Muglach, K., Culhane, J. L., Hara, H., & Watanabe, T. 2008, Astrophys. J., 686, 1362

Doschek, G. A., Warren, H. P., & Young, P. R. 2013, Astrophys. J., 767, 55

Feldman, U., Warren, H. P., Brown, C. M., & Doschek, G. A. 2009, Astrophys. J., 695, 36

Korendyke, C., et al. 2006, Applied Optics, 45, 8674

Kosugi, T., et al. 2007, Solar Physics, 243, 3

Lang, J., et al. 2006, Applied Optics, 45, 8689

Mariska, J. T., Warren, H. P., Williams, D. R., & Watanabe, T. 2008, Astrophys. J., 681, L41

Mariska, J. T., & Muglach, K. 2010, Astrophys. J., 713, 573

Warren, H. P., & Brooks, D. H. 2009, Astrophys. J., 700, 762

Warren, H. P., Brooks, D. H., & Winebarger, A. R. 2011, "Constraints on the Heating of High-Temperature Active Region Loops: Observations from Hinode and the Solar Dynamics Observatory", Astrophys. J., 734, 90

Warren, H. P., Kim, D. M., DeGiorgi, A. M., Ugarte-Urra, I. 2010, Astrophys. J., 713, 1095

Warren, H. P., Ugarte-Urra, I., Doschek, G. A., Brooks, D. H., & Williams, D. R. 2008b, Astrophys. J., 686, L131

Warren, H. P., Ugarte-Urra, I., Young, P.R., & Stenborg, G. 2011, "The Temperature Dependence of Solar Active Region Outflows", Astrophys. J., 727, 58

Warren, H. P., Winebarger, A. R., & Brooks, D. H. 2010, Astrophys. J., 711, 228

Warren, H. P., Winebarger, A. R., Mariska, J. T., Doschek, G. A., & Hara, H. 2008a, Astrophys. J., 677, 1395

Young, P. R., Doschek, G. A., Warren, H. P., & Hara, H. 2013, Astrophys. J., 766, 127

Young, P. R., Watanabe, T., Hara, H., & Mariska, J. T. 2009, Astron. & Astrophys., 495, 587

2000's.5: The Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER)

Contributed by Christoph R. Englert

1.0 Conception

The Spatial Heterodyne IMager for Mesospheric Radicals (SHIMMER) project was conceived as a result of conversations in 1993 between Prof. Fred L. Roesler (University of Wisconsin – Madison) and Robert (Bob) R. Conway of NRL/SSD. At that time, Conway was working on the Middle Atmosphere High Resolution Spectrograph Investigation (MAHRSI), which was going to measure middle atmospheric hydroxyl (OH) and nitric oxide (NO) density profiles using near UV solar resonance fluorescence from the Space Shuttle Cryogenic Infrared Spectrometer and Telescope for the Atmosphere-Shuttle Pallet Satellite (CRISTA-SPAS) platform. A key observational requirement for measuring OH was high spectral resolution to isolate the OH lines against a bright Rayleigh scattered background. Roesler was working on an innovative spectral technique called Spatial Heterodyne Spectroscopy (SHS) with his former graduate student Dr. John M. Harlander and realized that SHS offered a means to achieve this required spectral resolution using a dramatically smaller and lighter instrument than MAHRSI. Drs. Roesler and Conway quickly agreed to collaborate on developing the SHS concept for the near-ultraviolet (UV). The following two sections cover two space flight SHS experiments called SHIMMER that resulted from these initial discussions. The final paragraph provides some more detailed information on the SHS concept and how it works.

2.0 The SHIMMER-MIDDECK Experiment

After the two successful MAHRSI flights and a successful SHS OH instrument proof of concept in the laboratory, the SHIMMER team worked on an instrument for flight in the Space Shuttle mid-deck, where the "SHIMMER-MIDDECK" instrument would view the limb of the Earth through the side hatch window in order to measure the OH profile. Under the leadership of Dr. Conway, the instrument was built and after he retired in 2001, Joel G. Cordon (NRL/SSD), a long-time colleague of Conway, took over as the principal investigator for the MIDDECK flight. Under the leadership of Mr. Cardon, who previously had been in charge of the instrument characterization and testing, the SHIMMER-MIDDECK flight on STS-112 (October 2002) was successfully executed [Cardon et al., 2003]. The data was taken from about 330km altitude for a total of about 35 minutes, distributed over a short checkout period and two data taking periods. The core team for this effort was completed by Dr. Michael H. Stevens (NRL/SSD), Dr. Charles M. Brown (NRL/SSD), Ronen Feldman (Artep, Inc.), and John F. Moser (Artep, Inc.), all of whom were also part of the MAHRSI team, Drs. Roesler and Harlander, and Dr. Christoph R. Englert (NRL/SSD) who joined Conway's group in 1999.

Even though the instrument performed well for this flight and the characteristic OH signature was seen in the atmospheric data, no OH altitude profiles could be retrieved, most likely due to the fact that the side hatch window was contaminated during the time the orbiter was docked to the International Space Station. In spite of this difficulty, the data gathered during this flight demonstrated that SHS was indeed a very capable and suitable technique for this measurement.

3.0 SHIMMER on STPSat-1

In parallel to the SHIMMER-MIDDECK effort, the SHIMMER team developed an improved SHS interferometer for the measurement of OH using NASA funding. The new interferometer was no

longer comprised of individually mounted optical components, but it was a monolithic design, in which all components were optically contacted. This interferometer was virtually impossible to misalign, presenting a major advantage, considering the harsh vibration environment of space launches. Moreover, the monolithic design allowed for significant mass savings [Harlander et al., 2003].

In January 2002, Dr. Englert received a call from the DoD Space Test Program (STP) asking whether NRL could provide a SHIMMER payload, using the monolithic interferometer, for the upcoming STPSat-1 mission. The team concluded that by using major parts of the MAHRSI electronics, the "SHIMMER on STPSat-1" could be built within the given schedule and budget constraints. SHIMMER thus became the primary payload of STPSat-1. The STPSat-1 spacecraft was subsequently built by AeroAstro in Ashburn Virginia. The SHIMMER on STPSat-1 instrument was built, calibrated, and tested at NRL under the leadership of the principal investigator Dr. Englert and his team, predominantly comprised of the SHIMMER-MIDDECK team members.

STPSat-1 was launched on March 7, 2007 from Cape Canaveral on board an ATLAS V launch vehicle as part of STP-1, the first mission using an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) for launching multiple spacecraft. STPSat-1 was injected into a 560 km altitude and 35.4° inclination circular orbit and was operated for the first year from Kirtland Air Force Base in New Mexico. Subsequently, for an additional 1.5 years, it was operated by NRL from the Blossom Point Satellite Control and Tracking Station (Maryland) in collaboration with Tiger Innovations, LLC [Firestone et al., 2011]. SHIMMER data was archived and analyzed at the NRL Space Science Division. The STPSat-1 and SHIMMER missions ended on 7 October 2009. Parts of the SHIMMER project were supported by the DoD Space Test Program, ONR, and NASA.

Overall, the SHIMMER on STPSat-1 mission met its two primary mission objectives: (1) Demonstrate that Spatial Heterodyne Spectroscopy (SHS) is a technique that is suitable and offers advantages for long-duration space flight applications, and (2) measure middle atmospheric OH density profiles at low to mid latitudes and all daytime local times [Englert et al., 2008, 2010a; Stevens et al., 2009]. In addition, SHIMMER measured the diurnal variation of polar mesospheric clouds (PMCs) at the edge of their high latitude occurrence regions.

Major results from SHIMMER on STPSat-1 include:

- Establish first space flight heritage for an SHS instrument.
- Measurement of the seasonal variation of hydroxyl in the mesosphere [Englert et al., 2010a]
- Reconciliation of mesospheric HO_x chemistry [Conway et al., 2000; Englert et al., 2010a]
- Quantitative determination of local time dependence of PMCs at the edge of their occurrence region [Stevens et al., 2009, 2010]
- Verification of Navy Operational Global Atmospheric Prediction System – Advanced-Level Physics & High Altitude (NOGAPS-ALPHA) [Eckermann et al., 2009].

The flight of SHIMMER established SHS as a mature space flight technique and led to the development of other applications for SHS including an SHS prototype for the long wave infrared. Most significant, however, is the development of the Doppler Asymmetric Spatial Heterodyne (DASH) Spectroscopy technique, which is a slight modification of SHS [Englert et al., 2007, 2010b, Harlander et al., 2010, Englert et al., 2012]. DASH is an innovative technique to measure thermospheric winds, which are critically important for understanding and characterizing the Earth's ionosphere/thermosphere region. This region is of increasing national importance to both the civilian and military sector, since it influences medium and high frequency wave propagation in the upper atmosphere. In 2013, a DASH instrument named Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) was selected by NASA for flight on the Ionospheric Connection (ICON) Explorer mission. The ICON mission is led by the University of

California, Berkeley by the Principal Investigator (PI) Dr. Thomas Immel. NRL is responsible for the MIGHTI instrument under the leadership of Dr. Englert.

For his work on STPSat-1, Dr. Englert received the 2007 Department of the Navy Top Scientists and Engineers of the Year Award. The STPSat-1 team received the 2010 American Institute of Aeronautics and Astronautics Space Systems Award.

Figure 2000s.5.1 - SHIMMER-MIDDECK optics assembly. From the top left counterclockwise: Telescope, SHS interferometer mounted in a VascoMax steel cage, relay optics, CCD camera (credit: This figure first appeared in Cardon et al., 2003).

4.0 What Is Spatial Heterodyne Spectroscopy?

Spatial Heterodyne Spectroscopy (SHS) is a relatively novel concept that when compared to other spectroscopic techniques like Fabry-Perot or Michelson interferometers can offer many advantages for high spectral resolution diffuse-source spectroscopy. It was made possible primarily by the availability of detector arrays, e.g. the Charge Coupled Device (CCD), in combination with high computing speed to process the recorded interferogram data [Harlander at al., 1992].

In SHS, Fizeau fringes of wavelength-dependent spatial frequency are produced by a modified Michelson interferometer in which the return mirrors are replaced by conventional diffraction gratings (see Figure 2000s.5.2 and 2000s.5.4). The fringes, localized near the gratings, are recorded on a position sensitive detector (e.g. CCD) and Fourier transformed to recover the spectrum. Zero spatial frequency corresponds to the Littrow wavelength, which can be chosen by adjustment of the gratings. As a result high resolution spectra over a limited spectral range can be achieved with only modest requirements on the spatial resolution of the detector. In this process no element is mechanically scanned which enables the implementation of the monolithic concept.

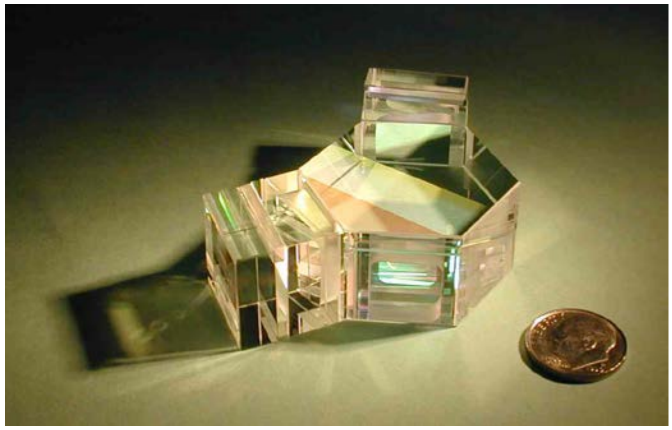

Figure 2000s.5.2 - Monolithic SHS interferometer for the near UV, flown as part of SHIMMER on STPSat-1. All elements are made of fused silica and optically contacted (credit: This figure first appeared in Harlander et al., 2004).

Figure 2000s.5.3 - Artist's conception of STPSat-1 on orbit (credit: AeroAstro).

SHS achieves a maximum resolving power equal to the theoretical resolving power of the dispersive (grating + prism) system while its field of view is characteristic of interferometric spectrometers. Furthermore, fixed field-widening prisms can be placed in the arms of the interferometer (see Figure 2000s.5.4) that enable SHS instruments to view even larger fields without degrading the resolving power. If the fringe pattern is imaged by N pixels in the dimension parallel to Figure 2000s.5.1, N/2 independent spectral elements may be recovered, independent of the resolution. An interference filter can be used to eliminate aliasing and multiplex noise from out-of-band light. Depending on the detector and optics before the interferometer, zero, one, or two dimensions of spatial information can be recorded.

SHS instruments have greatly relaxed alignment and surface figure tolerances when compared to scanning Fourier transform spectrometers (FTS) and Fabry-Pérot spectrometers (FPS). A detector located at the focal plane of lens L2 in Figure 2000s.5.4 integrates signal from the full aperture of the interferometer. In this case misalignments or figure errors in the interferometer of approximately one wavelength will greatly reduce the contrast of the fringes and degrade the signal to noise ratio of the spectrum. In SHS, the interferometer elements are nearly imaged on the detector resulting in each detector pixel integrating over a small area in the interferometer [Englert et al., 2006].

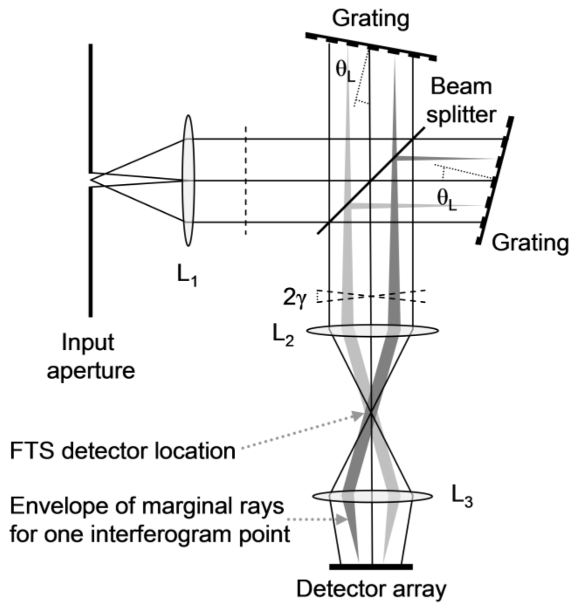

Figure 2000s.5.4 - Schematic diagram of the SHS configuration. For each wavelength in the incident wavefront, two wavefronts exit the interferometer with a wavelength-dependent crossing angle between them. This produces a superposition of Fizeau fringes with wavelength-dependent spatial frequencies localized near the gratings and imaged on the detector. The image is the Fourier transform of the input spectrum about the heterodyne wavelength (the wavelength producing parallel output wavefronts). The prism angles are chosen so that from a geometrical optics point of view the gratings appear coincident when viewed from the imaging detector (credit: This figure first appeared in Englert and Harlander, 2006).

References: 2000s.5: The Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER)

Cardon J.G., C.R. Englert, J.M. Harlander, F.L. Roesler, M.H. Stevens, SHIMMER on STS-112: Development and Proof-of-Concept Flight, AIAA Paper: 2003-6224, AIAA Space 2003 - Conference & Exposition, Long Beach, CA, Sept. 23-25, 2003.

Conway R. R., M. E. Summers, M. H. Stevens, J. G. Cardon, P. Preusse, and D. Offermann, Satellite observations of upper stratospheric and mesospheric OH: The HOx dilemma, Geophys. Res. Lett., 27(17), 2613–2616, doi:10.1029/2000GL011698, 2000.

Eckermann S.D., K.W. Hoppel, L. Coy, J.P. McCormack, D.E. Siskind, K. Nielsen, A. Kochenash, M.H. Stevens, C.R. Englert, M. Hervig, High-altitude data assimilation system experiments for the Northern Summer Mesosphere Season of 2007, Journal of Atmospheric and Solar–Terrestrial Physics, 71, 531-551, doi:10.1016/ j.jastp.2008.09.036, 2009.

Englert C.R. and J.M. Harlander, Flatfielding in Spatial Heterodyne Spectroscopy, Applied Optics, 45, 4583-4590, 2006.

Englert C.R., D.D. Babcock, J.M. Harlander, Doppler Asymmetric Spatial Heterodyne Spectroscopy (DASH): Concept and Experimental Demonstration, Applied Optics, 46, 7297-7307, 2007.

Englert C.R., M.H. Stevens, D.E. Siskind, J.M. Harlander, F.L. Roesler, H.M. Pickett, C. von Savigny, A.J. Kochenash, First Results from the Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER): Diurnal variation of mesospheric hydroxyl, Geophysical Research Letters, 35, L19813, doi:10.1029/2008GL035420, 2008.

Englert C. R., M. H. Stevens, D. E. Siskind, J. M. Harlander, and F. L. Roesler, Spatial Heterodyne Imager for Mesospheric Radicals on STPSat-1, J. Geophys. Res., 115, D20306, doi:10.1029/2010JD014398, 2010a.

Englert C.R., J.M. Harlander, J.T. Emmert, D.D. Babcock, F.L. Roesler, Initial thermospheric wind measurements using a ground-based DASH interferometer, Optics Express, 18, 27416-27430, 2010b.

Englert C.R., J.M. Harlander, C.M. Brown, J.W. Meriwether, J. J. Makela, M. Castelaz, J.T. Emmert, D.P. Drob, K.D. Marr, Coincident Thermospheric Wind Measurements using ground-based Doppler Asymmetric Spatial Heterodyne (DASH) and Fabry-Perot instruments, Journal of Atmospheric and Solar-Terrestrial Physics, 86, 92-98, doi:10.1016/j.jastp.2012.07.002, 2012.

Firestone D., R. Atkin, C. Hooks, C.R. Englert, D.E. Siskind, P.A. Bernhardt, C.L. Siefring, P.A. Klein, Low-Cost, Automated Ground Station for LEO Mission Support, IEEE Aerospace and Electronic Systems Magazine, 26, 12-18, doi:10.1109/MAES.2011.5746180, 2011.

Harlander J.M., R.J. Reynolds, and F.L. Roesler, "Spatial heterodyne spectroscopy for the exploration of diffuse interstellar emission lines at far-ultraviolet wavelengths," Astrophys. J. 396, 730–740 (1992).

Harlander J.M., F.L. Roesler, C.R. Englert, J.G. Cardon, R.R. Conway, C.M. Brown, J. Wimperis, Robust monolithic ultraviolet interferometer for the SHIMMER instrument on STPSat-1, Applied Optics, 42, 2829-2834, 2003.

Harlander J.M., F.L. Roesler, C.R. Englert, J.G. Cardon, J. Wimperis, Spatial Heterodyne Spectroscopy For High Spectral Resolution Space-Based Remote Sensing, Optics and Photonics News, Vol. 15, No. 1, 46-51, 2004.

Harlander J.M., C.R. Englert, D.D. Babcock, F.L. Roesler, Design and laboratory tests of a Doppler Asymmetric Spatial Heterodyne (DASH) interferometer for upper atmospheric wind and temperature observations, Optics Express, 18, 26430-26440, 2010.

Stevens M.H., C.R. Englert, S.V. Petelina, W. Singer, K. Nielsen, The diurnal variation of noctilucent cloud frequency near 55°N observed by SHIMMER, Journal of Atmospheric and Solar-Terrestrial Physics, 71, 401-407, doi:10.1016/j.jastp.2008.10.009, 2009.

Stevens M.H. et al., Tidally induced variations of PMC altitudes and ice water content using a data assimilation system, J. Geophys. Res., 115, D18209, doi:10.1029/2009JD13225, 2010.

2000's.6: NOGAPS-ALPHA: A Prototype Navy Global Numerical Weather Prediction System Extending from the Ground to the Edge of Space

Contributed by Stephen D. Eckermann

1.0 Introduction

The Navy is a global enterprise whose operations are impacted around the clock by weather. Naval history is littered with major incidents caused by unforeseen severe weather (e.g., recurrent damage to or losses of ships in hurricanes and typhoons). These realities underscore the need for a coordinated global operational numerical weather prediction (NWP) capability wholly dedicated to naval operations worldwide.

Efforts to provide this capability commenced in the late 1960s and early 1970s at the Naval Environmental Prediction Research Facility (NEPRF) in Monterey, California. NEPRF developed the first Navy Operational Global Atmospheric Prediction System (NOGAPS) as a 9-layer, $2.4^{o}x3^{o}$ configuration of the UCLA gridpoint general circulation model (GCM) of Arakawa and Lamb (1977). This inaugural NOGAPS went operational at the nearby Fleet Numerical Oceanography Center (FNOC) in August 1982 (Rosmond 1981). NOGAPS research and development (R&D) continued throughout the 1980s and 1990s at NEPRF, which later became the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) and, ultimately, the Marine Meteorology Division (MMD) of the Naval Research Laboratory (NRL). Major NOGAPS R&D milestones during this period were the replacement of the gridpoint GCM with a new state-of-the-art global spectral model (Hogan and Rosmond 1991), and the development of a multivariate optimum interpolation (MVOI) algorithm for operational analysis at FNOC (Barker 1992).

By the end of the 1990s, NOGAPS was already an established NRL success story, singled out as one of the 35 principal R&D highlights of the laboratory's first 75 years [see NRL's "Little Book of Big Achievements" (NRL 2000)]. In addition to serving as the backbone of the Navy's end-to-end weather prediction capability at the Fleet Numerical Meteorology and Oceanography Center (FNMOC), NOGAPS also became the backup global NWP system for the National Weather Service.

By the end of the century, NOGAPS was running operationally at FNMOC with triangular spectral truncation out to wavenumber 159 (T159), corresponding to an intrinsic latitude-longitude resolution of $\sim 1^{o}$, and 24 vertical model levels (L24). As shown in Figure 2000s.6.1i, this T159L24 formulation provided forecasts up to ~20 km altitude only (the upper levels in Figure 2000s.6.1i, colored orange, are heavily diffused in NOGAPS to absorb upward-propagating waves and so do not yield reliable forecasts).

2.0 Impetus to Extend NOGAPS Higher: The "Sky-High NOGAPS" Concept

As the new millennium approached, several emerging trends combined to pinpoint this ~20 km upper boundary in NOGAPS as a potentially serious restriction to future improvement and exploitation of NOGAPS forecasts for Navy and DoD users.

First, NRL was actively developing a next-generation successor to FNMOC's MVOI analysis system, a three-dimensional variational algorithm that later became known as the NRL Atmospheric Variational Data Assimilation System (NAVDAS: Daley and Barker 2001). One major new capability planned for NAVDAS was the ability to assimilate atmospheric radiances

acquired from operational satellite sensors directly into NOGAPS, rather than having to perform cumbersome offline temperature and humidity retrievals prior to the assimilation cycle. Nadir sounders, which provide most of the atmospheric data from operational meteorological satellites, have broad vertical weighting functions that can extend high into the stratosphere. A requirement for accurate radiance assimilation is accurate *a-priori* backgrounds from the forecast model at all atmospheric altitudes that contribute to these nadir radiances. Since the T159L24 NOGAPS provided forecasts up to ~20 km only, it could not provide the high-altitude forecast backgrounds necessary to exploit fully this important new NAVDAS capability.

Second, research was beginning to document major changes in Arctic winter weather that initiated in the stratosphere and subsequently descended to change surface conditions on hemispheric scales (Thompson and Wallace 1998). Though preliminary, these research findings had clear potential ramifications for global prediction, yet NOGAPS lacked the fully resolved stratosphere that would be necessary to model and capture such deep dynamical coupling pathways.

Third, new Navy/DoD assets were emerging that required knowledge of the “near space” environment (~10-100 km altitude). These included high-altitude long-endurance (HALE) airframes, boost-phase missile defense technologies, airborne laser weapon systems, high-altitude injection, transport and fallout of chemical, biological, radiological and nuclear (CBRN) material, and reentry of space vehicles and debris.

Thus, in early 1999, Dr. Simon Chang (NRL MMD Code 7530) canvassed support for a multidivisional NRL internal project to extend the upper boundary of NOGAPS to much higher altitudes. This became known as the “Sky-High NOGAPS” concept. Dr. Chang sought commitments from the Upper Atmospheric Physics Branch (NRL SSD’s UAP Code 7640) and the Remote Sensing Physics Branch (NRL Remote Sensing Division’s RSP Code 7220) to provide the human expertise to extend the NOGAPS model and data-assimilation components to higher altitudes.

At the time, UAP’s stratospheric and mesospheric research was based around a long tradition of measuring and modeling trace chemical constituents. The proposed Sky-High NOGAPS would represent a major change in UAP research direction, and it triggered intense debate within UAP, with strong opinions voiced for and against. Drs. Bob Meier (UAP Branch head) and Bob Conway (Code 7641 Section head) were both pivotal in providing management support for a small group of junior UAP scientists to sign on to Dr. Chang’s Sky-High NOGAPS vision. Dr. Conway’s support is especially laudable, since he allowed scientists within his section to move from his existing scientific research projects into this entirely new and uncharted R&D territory.

After a series of meetings in Monterey, CA and Washington, DC among key scientists from all three NRL divisions, a 4-year NRL new start proposal was formulated, presented by Dr. Chang to the NRL Research Advisory Committee (RAC) on 19 November 1999, and approved in early 2000. A kickoff workshop was held at NRL Monterey in September 2000.

3.0 An Advanced-Level Physics High-Altitude Forecast Model: NOGAPS-ALPHA

While the original intent was to extend the forecast model and data assimilation (DA) systems simultaneously, NAVDAS took longer to mature than initially projected, and so the initial NRL work focused mostly on a high-altitude forecast model. Due to ongoing confusion with another “SKYHI” GCM (Hamilton et al. 2001), NRL rebranded this prototype as “NOGAPS-ALPHA” (Advanced-Level Physics High-Altitude). The products of the initial 4-year NRL project to create NOGAPS-ALPHA are reviewed by Eckermann et al. (2004). A broader overview of forecast model development over the decade to 2010 is provided below, and is summarized schematically in Figures 2000s.6.1 and 2000s.6.2.

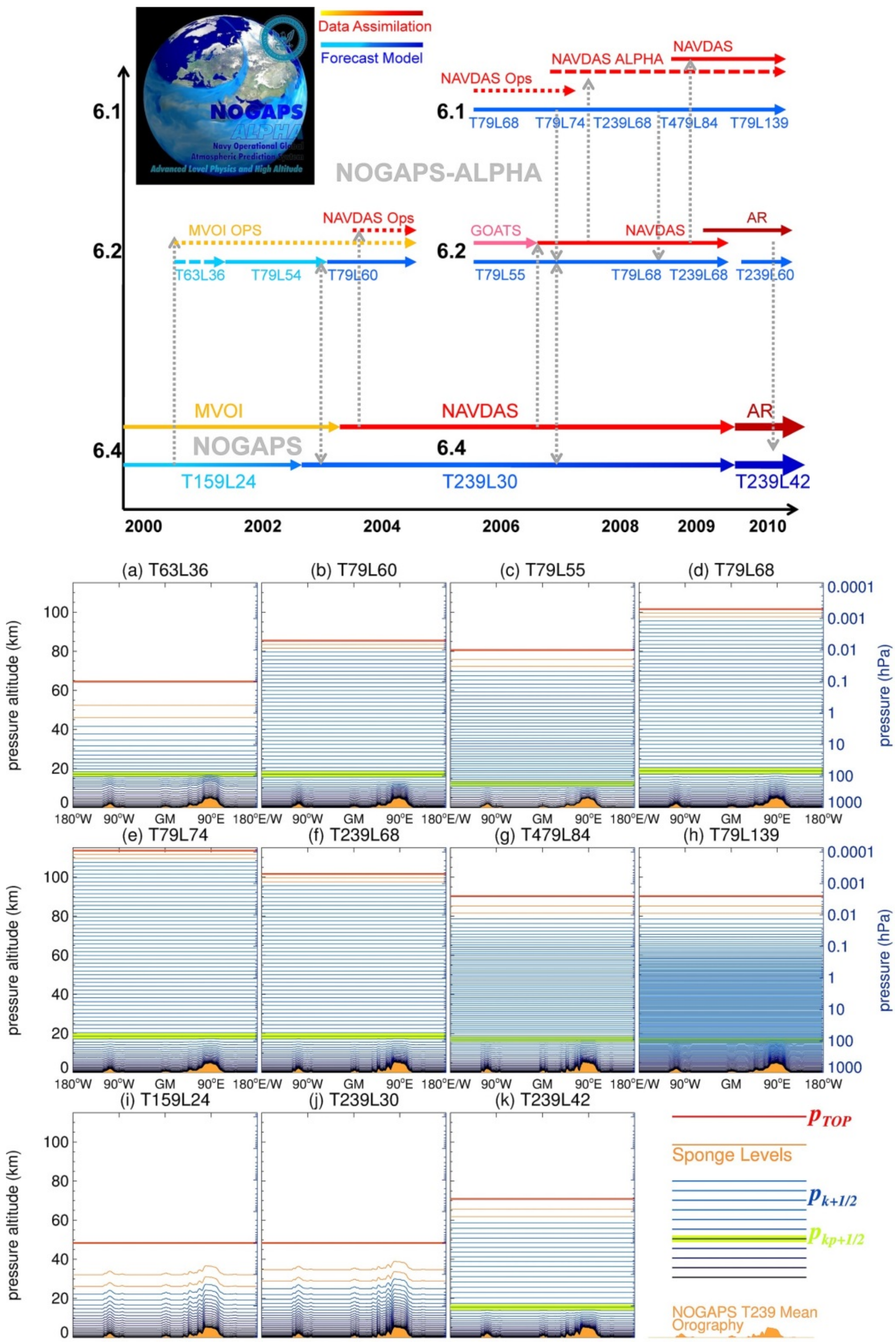

Figure 2000s.6.1 - Top panel depicts the R&D chronology of NOGAPS over the decade 2000-10, showing evolution of both the operational NOGAPS at FNMOC achieved via the 6.4 transition pathway, and of NOGAPS-ALPHA prototypes arising from in-house NRL research. Gray curves show times of key interactions between these 6.1-6.4 development streams in which NOGAPS-ALPHA developments impacted NOGAPS and/or vice versa. Various model prototypes labeled in that development matrix are depicted in panels (a)-(k) below. The presentation shows in each case the model topography at the indicated triangularly truncated spectral resolution (T63-479) around a 34.5^{o}N latitude circle and the various vertical model levels (L30-139). Model interface (half) levels $p_{k+1/2}$ are plotted in blue, with upper-level "sponge layers" containing increased dissipation to absorb upward propagating waves shown in orange, and the rigid upper boundary at pressure p_{TOP} marked in red. Green levels show $p_{kp+1/2}$, the lowest purely isobaric interface level in each case. The panels show examples of both R&D NOGAPS-ALPHA configurations (a)-(h) and operational NOGAPS configurations (i)-(k) (credit: NRL).

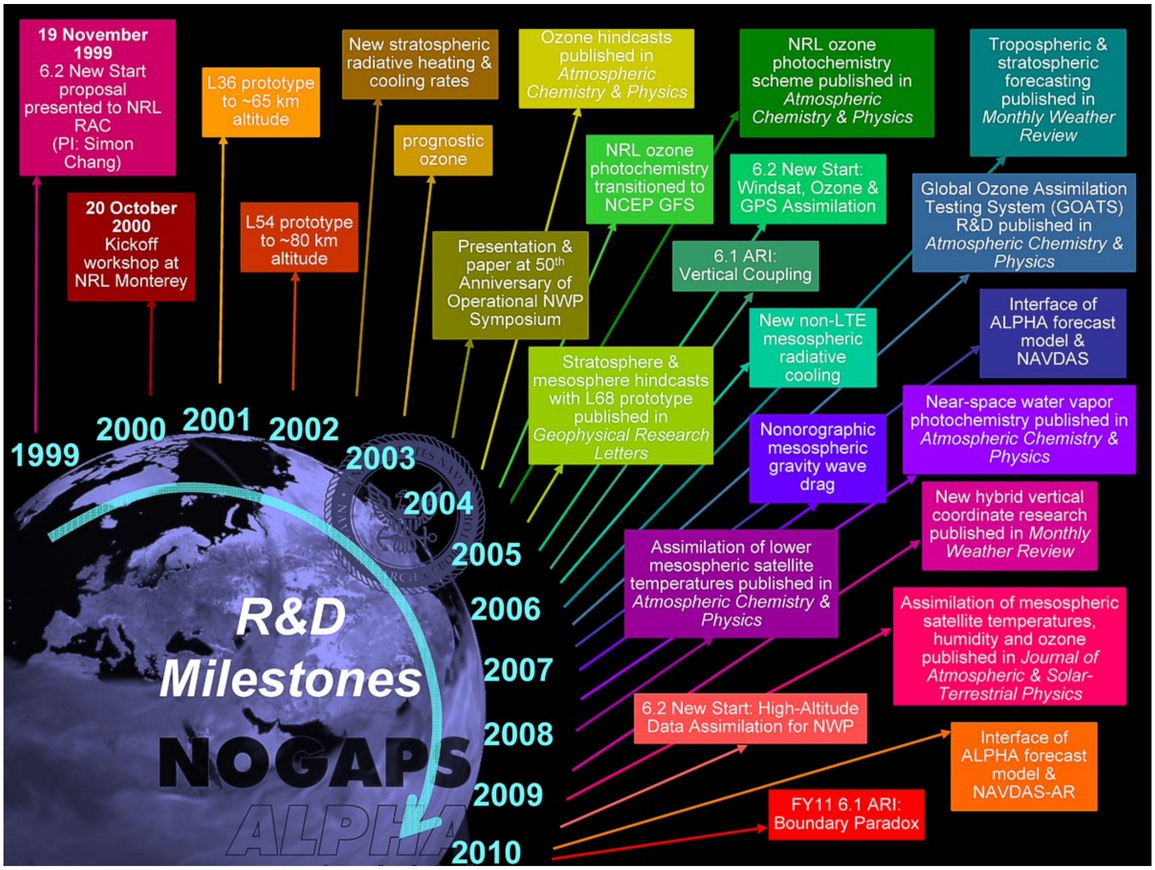

Figure 2000s.6.2 - A chronological summary of the major NOGAPS-ALPHA R&D milestones from 1999-2010 (see also Figure 2000s.6.1). See text for details (credit: NRL).

Upward extension of the forecast model progressed rapidly. As shown in Figures 2000s.6.1a-1f, a variety of new model configurations were created that extended significantly higher than the operational version. L36 (Kim and Hogan 2004), L54 (Eckermann et al. 2004; McCormack et al. 2004; Allen et al. 2006), L60 and L68 (Coy et al. 2005; Eckermann et al. 2006) configurations were issued in the early years and run at spectral resolutions ranging from T63 to T239, followed later by very high altitude (L74) and very high vertical resolution (L84, L139) configurations that ran at resolutions out to T479. The NOGAPS terrain-following σ vertical coordinate (see Figures 2000s.6.1i and 2000s.6.1j) was replaced in NOGAPS-ALPHA by a hybrid σ-p coordinate that transitioned smoothly from terrain-following layers near the ground to constant pressure surfaces in the stratosphere (10-50 km) and mesosphere (50-90 km). This substantially reduced vertical discretization errors over high terrain at the model's new upper levels (Eckermann 2009).

NOGAPS-ALPHA also required a range of new physical parameterizations to capture atmospheric physical processes relevant to NWP at its new upper levels.

Existing NOGAPS parameterizations of radiative shortwave heating (SWH) and longwave cooling (LWC) rates (Harshvardhan et al. 1987) were replaced with improved SWH and LWC parameterizations valid up to ~80 km (Chou and Suarez 1999; Chou et al. 2001). Later, the LWC rates above ~75 km were replaced by those from the scheme of Fomichev et al. (1998), which accounts for the breakdown of the local thermodynamic equilibrium (LTE) assumption for infrared CO_2 emissions at upper altitudes.

Given the key role of ozone in controlling the SWH and LWC of the stratosphere, an entirely new prognostic ozone capability had to be developed for NOGAPS-ALPHA. This began by expanding the forecast model dynamics to incorporate the initialization and global transport of a new ozone mixing-ratio variable. Since multiconstituent ozone photochemistry is prohibitively expensive within an NWP system, McCormack et al. (2006a) developed an efficient (yet accurate) linearized parameterization of ozone photochemistry for use in NOGAPS-ALPHA. The success of the McCormack ozone scheme saw it transition quickly into both NOGAPS and the Global Forecast System (GFS) of the National Centers for Environmental Prediction, where it had immediate positive impacts on ozone skill and in operational forecasts of surface UV indices (McCormack et al. 2006b). This approach was further generalized by McCormack et al. (2008) to provide a linearized parameterization of water vapor photochemistry for NOGAPS-ALPHA, which significantly improved humidity predictions above the tropopause. These prognostic NOGAPS-ALPHA ozone and humidity fields were passed to the SWH and LWC parameterizations to provide two-way interactive feedback between radiation and photochemistry in the forecast model. These additions made NOGAPS-ALPHA a state-of-the-art tool for radiative and photochemical research, leading, for example, to novel research papers on the global atmospheric response to a solar eclipse (Eckermann et al. 2007) and the effect of spatially variable ozone heating on the evolution of the winter stratosphere (McCormack et al. 2011).

Considerable effort was also devoted to the parameterization of subgrid-scale gravity-wave drag (GWD) at upper levels in NOGAPS-ALPHA. While Code 7500 focused on orographic GWD development, NRL/SSD focused on nonorographic GWD parameterizations for NOGAPS-ALPHA. After a number of candidate schemes were implemented and tested (see section 3d of Eckermann et al. 2004), a NASA-sponsored collaboration with global modelers at NASA and National Center for Atmospheric Research (NCAR) produced a "team scheme" for use in global models at each center (see Appendix of Eckermann 2011 for details). This led initially to the implementation of the 65-wave nonorographic GWD scheme of Garcia et al. (2007) in NOGAPS-ALPHA, as described by Eckermann et al. (2009). While accurate, that scheme also proved expensive, which motivated Eckermann (2011) to develop a single-wave stochastic analogue of that scheme that produced almost identical mean climate and analysis skill, but with a huge reduction in computational expense.

4.0 Coupling the NOGAPS-ALPHA Forecast Model to NAVDAS

Forecast models require accurate atmospheric initial conditions from observations, yet, while the NOGAPS-ALPHA forecast model developed rapidly, NAVDAS remained a work in progress, transitioning to FNMOC only at the end of 2003. Prior to this, for its 0-100 km initial conditions NOGAPS-ALPHA relied upon an *ad hoc* blending and extrapolation of operational and experimental analyses spanning various altitude ranges (see section 3c of Eckermann et al. 2004). Remarkably, despite these rudimentary early initial conditions, NOGAPS-ALPHA forecasts showed impressive skill in reproducing observed mesospheric evolution (e.g., Coy et al. 2005).

Nonetheless, the advent of NAVDAS motivated renewed interest in coupling it to the NOGAPS-ALPHA forecast model to provide state-of-the-art atmospheric analyses and initial conditions to high altitudes. Our initial foray into high-altitude data assimilation was limited in scope, beginning with a small side project led by Doug Allen in Code 7200 that focused on ozone assimilation. The resulting Global Ozone and Assimilation Testing System (GOATS) coupled a univariate ozone assimilation algorithm to the NOGAPS-ALPHA forecast model. GOATS proved very successful and provided valuable scientific insights into the coupling of ozone transport, photochemistry and observations within an NWP system (Coy et al. 2007).

The success of GOATS motivated renewed interest in taking on the bigger challenge of interfacing NAVDAS and NOGAPS-ALPHA. The concept was eventually made possible by an interdivisional

NRL new start led by Doug Allen that the RAC approved in early 2006. This yielded a T79L68 NOGAPS-ALPHA prototype interfaced to NAVDAS that, in addition to assimilating low-altitude operational sensor data, also assimilated temperature observations up to ~90 km altitude from research instruments on NASA's Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) and Aura satellites (Hoppel et al. 2008; Eckermann et al. 2009). This prototype became the first NWP system anywhere in the world to generate global meteorological DA products from the ground to the edge of space (~0-100 km altitude) – another remarkably successful NRL collaboration among Codes 7200, 7500 and 7600. While many individuals deserve credit, special mention must go to Karl Hoppel in Code 7200, who, when Dr. Allen left NRL soon after the NRL project commenced, became pivotal in getting this new system working, and to Dr. Nancy Baker and her DA section in NRL Code 7500 who provided critical NAVDAS support throughout. This unique new NRL capability, and the high-altitude analysis fields it produced, proved to be a scientific bonanza, spawning new scientific research into mesospheric responses to stratospheric warmings, planetary Rossby normal modes, mesospheric winds, tides, gravity waves, and polar mesospheric clouds (Hoppel et al. 2008; Eckermann et al. 2009; McCormack et al. 2009 2010; Nielsen et al. 2010; Stevens et al. 2010; Siskind et al. 2010; Coy et al. 2011; Sassi et al. 2012). That R&D work continued with the preliminary assimilation of mesospheric Special Sensor Microwave Imager/Sounder (SSMIS) radiances using NOGAPS-ALPHA in concert with the Navy's new four-dimensional variational DA algorithm, NAVDAS-AR (Accelerated Representor: Rosmond and Xu 2006).

5.0 The Future: NAVGEM, ESPC and Improved Navy NWP

The 10-year anniversary of the NOGAPS-ALPHA project in 2010 proved to be a significant milestone. Not only was the impact of NOGAPS-ALPHA on operational NWP finally fully realized, but this success also coincided with the graceful retirement of NOGAPS-ALPHA as a completed R&D project, as NRL research moved on to the development of the next generation of global NWP systems for the Navy.

Significant amounts of NOGAPS-ALPHA-enabled technology transitioned to FNMOC in September 2010 via an operational NOGAPS upgrade that was almost exclusively stratospheric. NOGAPS upgraded from L30 to L42, extending its vertical range from ~20 km to ~60 km (c.f. Figures 2000s.6.1j and 2000s.6.1k). This permitted assimilation of new stratospheric observations from GPS sensors and infrared and microwave nadir sounders, with some additional land/sea-ice channels also added. As shown in Figure 2000s.6.3, this largely stratospheric upgrade produced big increases in 0-5 day forecast skill *near the surface* (1000 hPa) in both hemispheres. Indeed, this improvement in surface forecast skill in Figure 2000s.6.3 was as large as any encountered at FNMOC since the initial transition from MVOI to NAVDAS in 2003. This provides objective verification of the large positive impact of the NOGAPS-ALPHA project on operational weather prediction for the Navy. In short, the NOGAPS-ALPHA project is a demonstrable NRL success story.

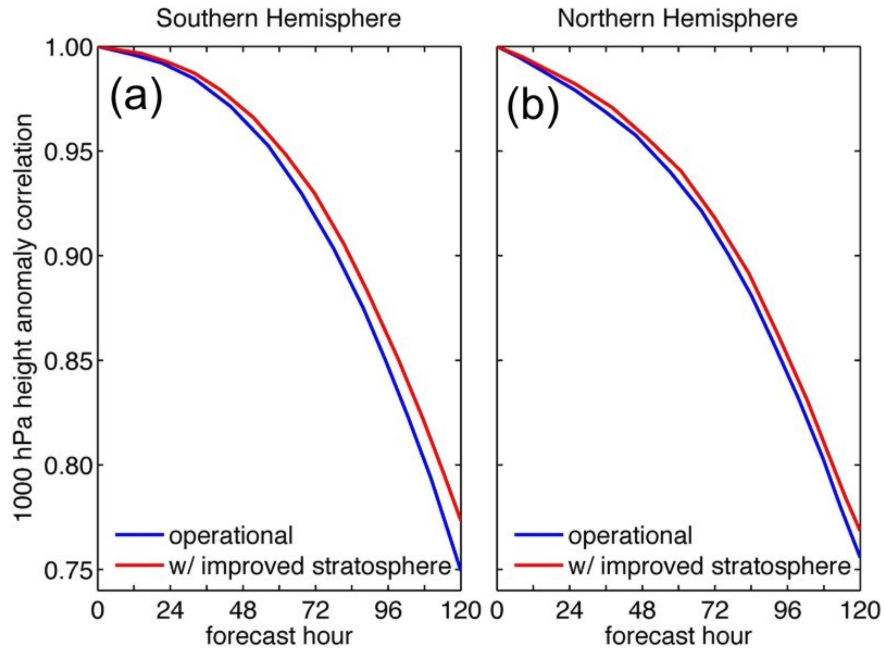

Figure 2000s.6.3 - Mean 1000 hPa geopotential height anomaly correlations (ACs) from 1 July to 6 September, 2010 in the (a) southern and (b) northern hemisphere using two versions of NOGAPS: (blue) the original σ-coordinate 30-level operational system that extended to ~30 km (See Figure 1j), and (red) a new hybrid σ-p 42-level system extending to ~70 km (see Figure 1k). Larger AC values indicate better objective forecast skill. Results were generated by Dr. Ben Ruston (NRL Code 7532). Figure is taken from Gerber et al. (2012) (credit: NRL).

Also in 2010, the Oceanographer of the Navy, RADM David Titley (Commander, Naval Meteorology and Oceanography Command (CNMOC)), began advocating for an Earth System Prediction Capability (ESPC), which he envisaged as a nationally coordinated multi-institutional enterprise to generate a seamless next-generation global prediction capability on time scales from days to decades. In October 2010, CNMOC hosted Navy stakeholders to develop courses of action (COAs) to "bridge" the gap between the current NWP capability (NOGAPS) and a projected ESPC in 2020. After a detailed cost-benefit analysis of over a dozen COA bridging strategies, CNMOC elected to develop a new Navy Global Environmental Model (NAVGEM) to replace NOGAPS at FNMOC as the Navy's bridge strategy to a future ESPC.

Accordingly, NOGAPS-ALPHA development was terminated at the end of 2010 and R&D resources were redirected to the development of a new semi-Lagrangian forecast model and four-dimensional DA components of NAVGEM, as a new FNMOC global NWP system slated to span the ~0-100 km altitude range. This new NAVGEM technology is heavily influenced by the NOGAPS-ALPHA experience, either via direct transfer of specific model components, or through the many lessons learned in building and benchmarking that system as the world's first 0-100 km prototype NWP system. With NAVGEM as the Navy's ESPC bridge, there is a new focus on extending forecasts out to seasonal scales, where the role of the stratosphere and mesosphere is increasingly important in regulating teleconnection pathways that affect surface weather on longer time scales (e.g., Baldwin et al. 2003; Inenson and Scaife 2009; NAS 2010; Gerber et al. 2012). Code 7600's institutional experience with NOGAPS-ALPHA is proving valuable in developing the NAVGEM upper levels that can make this system a state-of-the-art seasonal prediction system that paves the way for a future Navy ESPC. To that end, the inaugural T359L50 NAVGEM transitioned to operations at FNMOC on 13 February 2013 (Hogan et al. 2013), and the work of both MMD and SSD scientists in achieving this was formally recognized by the 2012 Department of the Navy Acquisition Excellence Technology Transition Award, presented by Assistant Secretary of the

Navy for Research, Development and Acquisition, Sean J. Stackley, on 14 May 2013.

References: 2000s.6: NOGAPS-ALPHA: A Prototype Navy Global Numerical Weather Prediction Extending from the Ground to the Edge of Space

Allen, D. R., L. Coy, S. D. Eckermann, J. P. McCormack, G. L. Manney, T. F. Hogan, and Y.-J. Kim (2006), NOGAPS-ALPHA simulations of the 2002 Southern Hemisphere stratospheric major warming, Mon. Wea. Rev., 134, 498-518.

Arakawa, A., and V. R. Lamb (1977), Computational design of the basic dynamical processes of the UCLA general circulation model. *Methods in Computational Physics: Advances in Research and Applications*, J. Chang, Ed., Academic Press, 173–265.

Baldwin, M.P., D.B. Stephenson, D.W.J. Thompson, T.J. Dunkerton, A.J. Charlton, A. O'Neill (2003), Stratospheric memory and extended-range weather forecasts, Science, 301, 636-640.

Barker, E. H. (1992), Design of the Navy's multivariate optimum interpolation analysis system. Wea. Forecasting, 7, 220–231.

Chou, M.-D., and M. J. Suarez (1999), A solar radiation parameterization for atmospheric studies, NASA Tech. Memo. NASA/TM-1999-104606, vol. 15, Technical Report Series on Global Modeling and Data Assimilation, edited by M. J. Suarez, 40 pp.

Chou, M.-D., M. J. Suarez, X.-Z. Liang, and M. M.-H. Yan (2001), A thermal infrared radiation parameterization for atmospheric studies, NASA Tech. Memo. NASA/TM-2001-104606, vol. 19, Technical Report Series on Global Modeling and Data Assimilation, edited by M. J. Suarez, 56 pp.

Coy, L., D. E. Siskind, S. D. Eckermann, J. P. McCormack, D. R. Allen, and T. F. Hogan (2005), Modeling the August 2002 minor warming event, Geophys. Res. Lett., 32, L07808, doi:10.1029/2005GL022400.

Coy, L., D. R. Allen, S. D. Eckermann, J. P. McCormack, I. Stajner, and T. F. Hogan (2007), Effects of model chemistry and data biases on stratospheric ozone assimilation, Atmos. Chem. Phys., 7, 2917-2935.

Coy, L., S. D. Eckermann, K. W. Hoppel, and F. Sassi (2011), Mesospheric precursors to the major stratospheric sudden warming of 2009: Validation and dynamical attribution using a ground-to-edge-of-space data assimilation system, J. Adv. Model. Earth Syst., 3, M10002, 7pp., doi:10.1029/2011MS000067.

Daley, R., and E. Barker, 2001: NAVDAS: Formulation and diagnostics. Mon. Wea. Rev., 129, 869–883.

Eckermann, S. D. (2009), Hybrid σ-p coordinate choices for a global model, Mon. Wea. Rev., 137, 224-245.

Eckermann, S. D. (2011), Explicitly stochastic parameterization of nonorographic gravity-wave drag, J. Atmos. Sci., 68, 1749-1765.

Eckermann, S. D., J. P. McCormack, L. Coy, D. Allen, T. Hogan, and Y.-J. Kim (2004), NOGAPS-ALPHA: A prototype high-altitude global NWP model, Paper P2.6, *Preprint Volume, Symposium on the 50th. Anniversary of Operational Numerical Weather Prediction*, American Meteorological Society, University of Maryland, College Park, MD, 14-17 June 2004, 23pp. http://geospace.nrl.navy.mil/dynamics/papers/Eckermann_P2.6.pdf

Eckermann, S. D., D. L. Wu, J. D. Doyle, J. F. Burris, T. J. McGee, C. A. Hostetler, L. Coy, B. N. Lawrence, A. Stephens, J. P. McCormack, and T. F. Hogan (2006), Imaging gravity waves in lower stratospheric AMSU-A radiances, Part 2: Validation case study, Atmos. Chem. Phys., 6, 3343-3362.

Eckermann, S. D., D. Broutman, M. T. Stollberg, J. Ma, J. P. McCormack, and T. F. Hogan (2007), Atmospheric effects of the total solar eclipse of 4 December 2002 simulated with a high-altitude global model, J. Geophys. Res., 112, D14105, doi:10.1029/2006JD007880.

Eckermann, S. D., K. W. Hoppel, L. Coy, J. P. McCormack, D. E. Siskind, K. Nielsen, A. Kochenash, M. H. Stevens, C. R. Englert, and M. Hervig (2009), High-altitude data assimilation system experiments for the northern summer mesosphere season of 2007, J. Atmos. Sol.-Terr. Phys., 71, 531-551.

Fomichev, V. I., J. P. Blanchet, and D. S. Turner (1998), Matrix parametrization of the 15 μm CO_2 band cooling in the middle and upper atmosphere for variable CO_2 concentration, J. Geophys. Res., 103, 11,505–11,528.

Garcia, R. R., D. R. Marsh, D. E. Kinnison, B. A. Boville, and F. Sassi (2007), Simulation of secular trends in the middle atmosphere, 1950–2003. J. Geophys. Res., 112, D09301, doi:10.1029/2006JD007485.

Gerber, E. P., A. Butler, N. Calvo, A. Charlton-Perez, M. Giorgetta, E. Manzini, J. Perlwitz, L. M. Polvani, and F. Sassi (2012), Assessing and understanding the impact of stratospheric dynamics and variability on the Earth system, Bull. Am. Meteorol. Soc., 93, 845-859.

Hamilton, K., R. J. Wilson, and R. S. Hemler (2001), Spontaneous stratospheric QBO-like oscillations simulated by the GFDL SKYHI general circulation model. J. Atmos. Sci., 58, 3271–3292.

Harshvardhan, R. Davies, D. Randall, and T. Corsetti (1987), A fast radiation parameterization for atmospheric circulation models, J. Geophys. Res., 92, 1009-1016.

Hogan, T. F., and T. E. Rosmond (1991), The description of the Navy Operational Global Atmospheric Prediction System's spectral forecast model. Mon. Wea. Rev., 119, 1786–1815.

Hogan, T., M. Peng, N. Baker, C. Reynolds, B. Ruston, M. Liu, J. Ridout, S. Eckermann, J. Moskaitis, T. Whitcomb, K. Viner, J. McLay, P. Pauley, L. Xu., R. Langland, M. Flatau, J. McCormack, and S. Chang (2013), The Navy Global Environmental Model, 2013 NRL Review, in press.

Hoppel, K. W., N. L. Baker, L. Coy, S. D. Eckermann, J. P. McCormack, G. E. Nedoluha, and D. E. Siskind (2008), Assimilation of stratospheric and mesospheric temperatures from MLS and SABER into a global NWP model, Atmos. Chem. Phys., 8, 6103-6116.

Ineson, S., and A. A. Scaife (2009), The role of the stratosphere in the European climate response to El Niño, Nat. Geosci., 2, 32–36.

Kim, Y-J., and T. F. Hogan (2004), Response of a global atmospheric forecast model to various drag parameterizations. Tellus, 56A, 472–484.

McCormack, J. P., S. D. Eckermann, L Coy, D. R. Allen, Y.-J. Kim, T. Hogan, B. N. Lawrence, A. Stephens, E. V. Browell, J. Burris, T. McGee, and C. R. Trepte (2004), NOGAPS-ALPHA model simulations of stratospheric ozone during the SOLVE2 campaign, Atmos. Chem. Phys., 4, 2401-2423.

McCormack, J. P., S. D. Eckermann, D. E. Siskind, and T. J. McGee (2006a), CHEM2D-OPP: A new linearized gas-phase ozone photochemistry parameterization for high-altitude NWP and climate models, Atmos. Chem. Phys., 6, 4943-4972.

McCormack, J. P., T. F. Hogan, C. Long, M. Iredell (2006b), New NRL photochemistry model improves NCEP ozone forecasts, JCSDA Quarterly, No. 15 (June 2006), 2-3.

McCormack, J. P., K. W. Hoppel, and D. E. Siskind (2008), Parameterization of middle atmospheric water vapor photochemistry for high-altitude NWP and data assimilation, Atmos. Chem. Phys., 8, 7519-7532.

McCormack, J. P., L. Coy, and K. W. Hoppel (2009), Evolution of the quasi-2 day wave during January 2006, J. Geophys. Res., 114, D20115, doi:10.1029/2009JD012239.

McCormack, J. P., S. D. Eckermann, K. W. Hoppel, and R. A. Vincent (2010), Amplification of the quasi-two day wave through nonlinear interaction with the migrating diurnal tide, Geophys. Res. Lett., 37, L16810, doi:10.1029/2010GL043906.

McCormack, J. P., T. R. Nathan, and E. C. Cordero (2011), The effect of zonally asymmetric ozone heating on the Northern Hemisphere winter polar stratosphere, Geophys. Res. Lett., 38, L03802, doi:10.1029/2010GL045937.

Nielsen, K., D. E. Siskind, S. D. Eckermann, K. W. Hoppel, L. Coy, J. P. McCormack, S. Benze, C. E. Randall, and M. E. Hervig (2010), Seasonal variation of the quasi 5 day planetary wave: Causes and consequences for polar mesospheric cloud variability in 2007, J. Geophys. Res., 115, D18111, doi:10.1029/2009JD012676.

NAS (2010), Assessment of intraseasonal and interannual climate prediction and variability, Committee on Assessment of Intraseasonal to Interannual Climate Prediction and Predictability, National Research Council, The National Academies Press, 192pp (http://www.nap.edu/catalog.php?record_id=12878).

NRL (2000), *The Little Book of Big Achievements*, S. Oresky and D. DeYoung eds., NRL/PU/1001--99-393, March 2000, 28pp.
http://www.nrl.navy.mil/media/publications/little-book-of-big-achievements/

Rosmond, T. E. (1981), NOGAPS: Navy Operational Global Atmospheric Prediction System. *Preprint Vol. Fifth Conference on Numerical Weather Prediction*, American Meteorological Society, Monterey, California, 2-6 November, p74-79.

Rosmond, T., and L. Xu (2006), Development of NAVDAS-AR: Non-linear formulation and outer loop tests, Tellus, 58A, 45–58.

Sassi, F., R. R. Garcia, and K. W. Hoppel (2012), Large-scale Rossby normal modes during some recent northern hemisphere winters, J. Atmos. Sci., 69, 820-839.

Siskind, D. E., S. D. Eckermann, J. P. McCormack, L. Coy, K. W. Hoppel, and N. L. Baker (2010), Case studies of the mesospheric response to recent minor, major, and extended stratospheric warmings, J. Geophys. Res., 115, D00N03, doi:10.1029/2010JD014114.

Stevens, M. H., D. E. Siskind, S. D. Eckermann, L. Coy, J. P. McCormack, C. R. Englert, K. W. Hoppel, K. Nielsen, A. J. Kochenash, M. E. Hervig, C. E. Randall, J. Lumpe, S. M. Bailey, M. Rapp, P. Hoffmann, and J. Fiedler (2010), Tidally induced variations of polar mesospheric cloud altitudes and ice water content using a data assimilation system, J. Geophys. Res., 115, D18209, doi:10.1029/2009JD013225.

2000's.7: The Remote Atmospheric and Ionospheric Detection System (RAIDS)

Contributed by Scott A. Budzien and Andrew W. Stephan

1.0 Introduction

The Remote Atmospheric and Ionospheric Detection System (RAIDS) is an experiment for studying the Earth's thermosphere and ionosphere from a vantage point on the International Space Station (ISS). The RAIDS sensor suite includes eight optical sensors which span the extreme-ultraviolet to near-infrared wavelength range (55-874 nm) and remotely sense the thermosphere and ionosphere by scanning and imaging the atmospheric limb. The RAIDS experiment has a long history extending over thirty years, with roots that run deep within the NRL Space Science Division. The RAIDS experience highlights both the challenges and benefits inherent in developing and flying a large, monolithic experiment with broad measurement capabilities. Ultimately, the RAIDS experiment provides an excellent example of repurposing high-quality spaceflight hardware to address new problems and remain scientifically and technically relevant, even after years of delays.

RAIDS and a companion NRL experiment, the Hyperspectral Imager for Coastal Ocean (HICO), were sponsored by the DoD Space Test Program (STP) and integrated into the eponymous HICO-RAIDS Experiment Payload (HREP). HREP was the first US payload designed for the ISS Japanese Experiment Module Exposed Facility (JEM-EF) and served as a pathfinder for developing US payloads for this new space facility. HREP flew on the maiden voyage of both Japan's new H-IIB launch vehicle and the *Kountori* H-II Transfer Vehicle (HTV) unmanned cargo transport. HREP was launched from Tanegashima Space Center, Japan in September 2009, installed on the space station, and now operates in a NASA-allocated berth on the JEM-EF. RAIDS itself serves as a pathfinder demonstrating atmospheric remote sensing from the ISS, and the experiment has provided new insights into the temperature of the lower thermosphere, extreme ultraviolet ionospheric sensing techniques, and the local time dependence of the chemically and thermodynamically important gas nitric oxide.

2.0 RAIDS Development

Dr. George Mount of NRL/SSD, the first RAIDS PI, and others in the Upper Air Branch of the NRL Space Science Division conceived the project in 1983, when global remote sensing of the thermosphere and ionosphere for operational space weather sensing was a truly innovative concept. The state of the art at that time relied on the limited data available to stitch together a global picture of the thermosphere-ionosphere system. Scientists at NRL had made a number of ground-breaking advances in developing novel methods for ultraviolet remote sensing of this region of the atmosphere with various sounding rockets, satellites, and lunar missions, but measurements were limited in global, temporal, or spectral coverage. The RAIDS experiment was developed to perform the first comprehensive global satellite survey of the upper atmosphere using hyperspectral remote sensing of airglow, and to demonstrate advanced global remote sensing methods for operational space weather monitoring. Dr. Mount and Army Capt. Dr. Robert McCoy briefed RAIDS to STP at the Navy and DoD Space Experiment Review Board, where the experiment received high-level support from both the Navy and Air Force as a pathfinder for UV remote sensing as a promising space weather technology.

Dr. Mount retired in 1985 and Dr. McCoy, having joined NRL/SSD, assumed the role of RAIDS PI, a position he would hold until 2006. In 1986 STP identified a launch opportunity for RAIDS as

a secondary payload aboard either the *NOAA-I* or *NOAA-J* Television Infrared Observation Satellite (TIROS) weather satellites. During the period from 1986 to 1990 the RAIDS program involved a large number of NRL Space Science Division employees, contractors, and students as RAIDS development ramped up. The RAIDS experiment (Fig. 2000s.7.1) was built under a joint partnership between NRL and The Aerospace Corporation (El Segundo, CA). NRL built the flight electronics and designed a technologically advanced far ultraviolet (FUV) imaging spectrograph while Aerospace built the limb scanning mechanism and structure and contributed a similarly-advanced extreme-ultraviolet (EUV) imaging spectrograph. The other six spectrometers and filter photometers were procured from Research Support Instruments, Inc. (Cockeysville, MD) based upon rugged designs flown aboard sounding rockets. Other organizations involved in the support, development, and sponsorship of RAIDS include the Space and Naval Warfare Systems Command (SPAWAR), the Defense Meteorology Satellite Program (DMSP), STP, and the Office of Naval Research (ONR). Many of those scientists and engineers went on to become prominent members of the blossoming aeronomy and space weather community before the RAIDS mission would finally launch.

Two challenging issues dominated the early development of the RAIDS experiment: a continuous upward creep of the mass budget for the mechanical design and concerns about electromagnetic interference with the TIROS rescue beacon system. Of the two launch opportunities identified for RAIDS, *NOAA-I* satellite was slated for a morning orbit (less desirable for the RAIDS mission) and an earlier launch schedule, but had more mass margin for secondary payloads. *NOAA-J* was scheduled for an afternoon orbit, but had less mass margin. The electromagnetic interference was resolved by NRL, and the larger mass allocation was eventually accepted by the TIROS program. However, the mass of RAIDS would ultimately play a pivotal role in the drama which ensued.

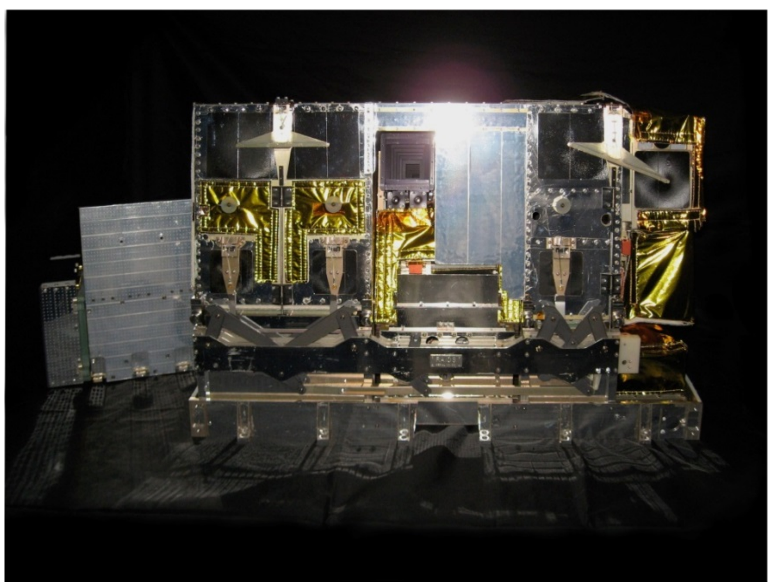

Figure 2000s.7.4 - The RAIDS hyperspectral experiment after refurbishment in 2009 included eight optical sensors spanning the near infrared to extreme ultraviolet passband in the large scan head (right) and a separate radiatively-cooled near-infrared detector box (left) (credit: NRL).

3.0 Launch Opportunities

The RAIDS sensor suite was built, delivered, tested, and integrated onto a TIROS satellite in 1992 in preparation for the *NOAA-J* mission. When the *NOAA-I* satellite failed a few weeks after reaching orbit, RAIDS appeared to have dodged a bullet by opting to fly on the following satellite. However, the subsequent TIROS mission was then reconfigured to replace the failed satellite, and a

Solar Backscatter Ultraviolet ozone instrument (SBUV/2) was added, putting the satellite over its mass allocation. RAIDS, as a secondary payload, was de-integrated from TIROS in 1994 and was placed in clean storage at NRL. Eleven domestic and foreign launch opportunities were pursued over the course of thirteen years, each ultimately frustrated by spacecraft accommodation of the large RAIDS sensor suite, programmatic issues, or simple bad luck.

Three of the unsuccessful launch opportunities examples are worth mention. First, in 1995 NRL responded to a NASA Middle-class Explorer (MIDEX) mission opportunity with the Thermospheric and Ionospheric Global Remote Sensing (TIGERS) Mission centered upon the RAIDS sensor suite. The proposal was selected for study, but when Congress restored funding for the NASA Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) mission, TIGERS was cancelled. Later, an accommodation study was undertaken for a launch opportunity available on a dedicated Small Explorer, SMEX-Lite, satellite bus developed at NASA Goddard. However, in 1998 the bus was allocated to *Triana*, the Earth imaging mission envisioned and promoted by Vice President Al Gore. In 2004 the team pursued an opportunity with the Indian Space Research Organisation (ISRO). A number of high-level meetings were held, including a letter of support by the Indian Prime Minister, but ultimately, the US State Department declined to support the mission.

4.0 New Opportunity, New Mission, New Challenges

In October 2006, STP identified a new flight opportunity for RAIDS on the ISS. Dr. Scott Budzien of the NRL/SSD assumed the role of PI from Dr. McCoy, who had joined ONR, and Dr. Scott Budzien began the process of evaluating and refocusing the RAIDS mission objectives for this new opportunity. In March 2007 RAIDS was once again manifested, this time to fly with HICO as part of HREP.

HREP was set to launch aboard a demonstration flight of a new Japanese unmanned cargo delivery system that would dock to a module not then installed on the ISS. The two science experiments would operate inside the modular HREP payload, a structure approximately the size of a refrigerator that would provide power and communications between the experiments and the ISS. The deadline for delivery of the experiments loomed less than two years away, and the funding available for the mission was extremely limited. The payload would have to be designed and interfaced to multiple vehicles/facilities in space, with some documents not yet translated from Japanese. The procedures for developing and delivering a US payload for Japanese integration, launch, and installation were not fully defined, and thus the HREP mission was to serve as a pathfinder to work out these kinks.

The new RAIDS mission aboard the ISS was streamlined for a short schedule and for minimum acquisition cost, while necessarily accepting higher performance risk. The development, test, and integration schedule was extremely compressed: only 23 months were allotted from program kickoff to delivery in February 2009 to meet the original target launch date. The launch date would slip by only 3 months during the program. Neither the HREP payload infrastructure nor the HICO experiment was designed at the beginning of the program; RAIDS was in a better position as pre-existing hardware. Even so, the extended storage period created new challenges for evaluating, refurbishing, testing, and integrating RAIDS within the allotted time. Tight budget constraints affected decision-making at both the experiment- and payload-levels.

In the face of these significant challenges, the NRL Remote Sensing Division, Space Science Division, and Naval Center for Space Technology undertook the HREP mission. RAIDS underwent a fast-paced, 18 month hardware modification program to prepare for the ISS mission. The extant RAIDS experiment package had been built to approximately Class-B (Medium Risk with Cost-Saving Compromises) specifications, but the RAIDS refurbishment and the overall

HREP program was defined as Class-D (Minimum Acquisition Cost). Class-D space missions typically include characteristics such as small size, low cost, short life, low complexity, medium to high risk, single-string designs, no flight spares, and relaxed testing requirements with respect to payload performance. Nevertheless, as an ISS payload, all HREP hardware still had to satisfy both the NASA and the Japanese Aerospace Exploration Agency (JAXA) manned spaceflight safety requirements, without exception. For this and other reasons, the HREP mission was considered high-risk and was closely monitored by NRL management. Fortunately, NRL had the requisite experience, facilities, and talented personnel to meet the challenges and exceed expectations. With extensive support from STP and the NASA ISS payload development office, both of which were essential to mission success, the HREP payload was delivered on-time.

5.0 RAIDS Science

The RAIDS team reconceived the scientific goals of the program in light of both the observational constraints of the ISS and 15 years of progress in ionosphere-thermosphere research. The lower 51.6° orbital inclination precluded high-latitude and auroral measurements, and the 330-425 km ISS orbital altitude eliminated some of the original RAIDS targets in the upper ionosphere and thermosphere. Due to the tight schedule and budgetary constraints, the team adopted a conservative plan for defining cutting edge science that could be performed with the fewest modifications to the RAIDS hardware.

The team identified three primary objectives of the refocused RAIDS mission:

1) Measure temperatures in the lower thermosphere (100–200 km) that encompasses the transition from the coldest part of the atmosphere at the mesopause near 85 km, up to the hottest regions of the thermosphere above 300 km.
2) Observe the photoionization process of atomic oxygen in the lower thermosphere that serves as the source of extreme ultraviolet photons that illuminate the daytime ionosphere from below.
3) Measure composition and chemistry of the lower thermosphere and ionosphere.

These goals targeted an important but sparsely measured region of the near-Earth space environment that has an operational impact on Navy and DoD systems. In addition to serving as a protective interface between precipitating energetic particles and ionizing solar radiation and the Earth's lower atmosphere, the transition region in the lower thermosphere represents the medium through which disturbances from below can propagate upward. These perturbations drive changes in the ionosphere and thermosphere, where satellites orbit and manned space systems operate and through which navigation, communication, and other electromagnetic signals traverse.

6.0 Results

RAIDS was successfully launched to the ISS on Sep. 9, 2009 and began science operations on October 23 (Fig. 2000s.7.2). Within the first six months of operation, RAIDS had collected sufficient data to complete all of its primary objectives. While the data will provide new results for years to come, some important scientific highlights have already come from the mission:

1) A comparison of temperatures obtained from RAIDS to those obtained from the NASA *Thermophere Ionosphere Mesophere Energetic and Dynamics* explorer satellite Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) experiment has validated the RAIDS method of using space-based observations of the O_2 Atmospheric band to determine temperatures in the lower thermosphere, providing new capability across a wider range of altitudes in the lower thermosphere.

2) A comparison between a model for photoionization of atomic O in the lower thermosphere, and RAIDS measurements of the altitude profile of the associated OII 61.7 nm emission has unraveled part of the complex relationship between neutrals and ions in interpreting airglow signals for characterizing the daytime ionosphere. The results from this comparison are being used to improve operational algorithms.
3) A study of the local time variability of nitric oxide (NO), as measured for the first time by RAIDS, has validated our current understanding of chemistry of this species. NO is an important participant in the energy balance within the upper atmosphere.

The temperature sensing method and the 61.7/83.4 nm daytime ionosphere sounding method demonstrated by RAIDS are being incorporated in NASA's new Ionosphere Connection (ICON) explorer mission planned for a 2017 launch.

Figure 2000s.7.5 - The gold-blanketed RAIDS experiment views the atmosphere aftward from the open end of the HREP while attached to the Japanese Experiment Module Exposed Facility (JEM-EF) (credit: NASA).

The RAIDS experiment operated for over 14 months before an apparent failure of the scan drive electronics rendered the platform immobile. However, the RAIDS instruments continue to operate and collect nadir-viewing data after more than three years of life on-orbit. During this time, RAIDS has provided vital information for NRL, DoD, and the scientific community considering future sensors with the ISS as an observing platform:

1) The RAIDS mission provided extensive scientific and technical knowledge and experience for understanding methods and techniques to ensure operation of sensors on the ISS, including an extensive database on ISS pointing and attitude and the nuances associated with interpreting the data.
2) The RAIDS data have demonstrated that optics sensitive to particulate and hydrocarbon contamination can still successfully operate for an extended period of time on the ISS.
3) The RAIDS experiment and HREP program served as a pathfinder for negotiating the cooperation between national and international agencies necessary to support the deployment and operation of experiments on a multi-use platform like the ISS.

Perhaps most importantly, the success of the RAIDS experiment proved a testament to the robust design and development from the original team members, and the resourcefulness of the new team in repurposing a scientifically cutting-edge experiment from the past into a successful, modern pathfinder engineering and innovative scientific program.

References: 2000s.7: The Remote Atmospheric and Ionospheric Detection System (RAIDS)

Bishop, R. L., S. A. Budzien, J. H. Hecht, A. W. Stephan, A. B. Christensen, P. R. Straus, Z. Van Epps 2009, "The Remote Atmospheric and Ionospheric Detection System on the ISS: Sensor Performance and Space Weather Applications from the Visible to the Near Infrared", Solar Physics and Space Instrumentation III, Proc. SPIE, **7438**, 0Z1-0Z12.

Budzien, S. A., A. W. Stephan, R. L. Bishop, A. B. Christensen, and K. R. Minschwaner 2011, “The RAIDS experiment on the ISS: on-orbit performance”, Solar Physics and Space Weather Instrumentation IV, Proc. SPIE, **8148**, 814805 1-12, doi:10.1117/12.893962.

Budzien, Scott A., Rebecca L. Bishop, Andrew W. Stephan, Andrew B. Christensen, and Donald R. McMullin 2010, "Atmospheric Remote Sensing on the International Space Station", EOS Trans. A.G.U., **91**, 381-382.

Christensen, A. B., R. L. Bishop, S. A. Budzien, J. H. Hecht, M. G. Mlynczak, J. M. Russell III, A. W. Stephan, R. W. Walterscheid 2013, "Altitude profiles of lower thermospheric temperature from RAIDS/NIRS and TIMED/SABER remote sensing experiments", J. Geophys. Res., doi:10.1002/jgra.50317.

Christensen, A. B., J.-H. Yee, R. L. Bishop, S. A. Budzien, J. H. Hecht, G. Sivjee, and A. W. Stephan 2012, "Observations of molecular oxygen Atmospheric band emission in the thermosphere using the near infrared spectrometer on the ISS/RAIDS experiment", J. Geophys. Res., **117**, A04315, doi:10.1029/2011JA016838.

Douglas, E. E., S. M. Smith, A. W. Stephan, L. Cashman, S. Chakrabarti, R. L. Bishop, S. A. Budzien, A. B. Christensen, and J. H. Hecht 2012, "Evaluation of Ionospheric Densities Using Coincident OII 83.4 nm Airglow and The Millstone Hill Radar", J. Geophys. Res., **117**, A0533, doi:10.1029/2012JA017574.

Stephan, A. W., J. M. Picone, S. A. Budzien, R. L. Bishop, A. B. Christensen, and J. H. Hecht 2012, "Measurement and application of the O II 61.7 nm dayglow", J. Geophys. Res., **117**, A1, doi:10.1029/2011JA016897.

Stephan, A. W., A. B. Christensen, S. A. Budzien, R. L. Bishop, and J. H. Hecht 2011. “Characterization of sensitivity degradation seen from the UV to NIR by RAIDS on the International Space Station”, Solar Physics and Space Weather Instrumentation IV, Proc. SPIE, **8148**, 814804, doi:10.1117/12.894093 1-11.

2000's.8: The Tiny Ionospheric Photometer (TIP) for the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC)

Contributed by Kenneth F. Dymond

1.0 Introduction

The *Constellation Observing System for Meteorology, Ionosphere, and Climate* (*COSMIC*) satellite constellation is a collaborative science mission between the United States and the Republic of China (Taiwan) focused upon meteorology, ionospheric science, climate, and geodesy. On April 14, 2006 six *COSMIC* microsatellites were successfully launched from Vandenberg Air Force Base aboard an Orbital Sciences Minotaur launch vehicle into low Earth orbit with identical payloads consisting of a Global Positioning System (GPS) radio occultation sounder, the Tiny Ionospheric Photometer (TIP) a small ultraviolet photometer, and a Tri-band radio Beacon (TBB). The six satellites initially flew sequentially like beads on a string in a single 515-km, 72°-inclination orbit. Over the first 18 months of the mission, the satellites were individually raised into six 800 km orbits separated by 24° at the ascending nodes to attain uniform global coverage. The primary payload of each *COSMIC* satellite is a GPS Occultation Experiment (GOX), a GPS receiver developed by the National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL). By measuring the phase delay of radio waves from GPS satellites as they are occulted by the Earth's atmosphere, accurate and precise vertical profiles of the bending angles of radio wave trajectories are obtained in the ionosphere, stratosphere, and troposphere. The atmospheric refractivity in the troposphere, used to infer either water vapor density profile or temperature profile for tropospheric weather forecasting, is determined from the bending angle measurements. Additionally, the *COSMIC* satellites also measure the refractivity in the ionosphere which is inverted to produce electron density profiles [Anthes et al., 2008].

The satellites were flown and operated by the National Space Organization (NSPO) in Taiwan, where the mission was referred to as *Formosa Satellite Mission #3* (*FORMOSAT-3*). The mission is known as *COSMIC* in the US, where the University Corporation for Atmospheric Research (UCAR) administers the program. The *COSMIC*/*FORMOSAT-3* (*CF3*) system acquired between 1400 and 2300 good quality GPS occultations per day [Anthes et al., 2008], characterizing weather in the lower atmosphere and measuring electron density in the ionosphere. These data are archived in data centers in Taiwan and Boulder, Colorado and used by several weather agencies worldwide. The U.S. Naval Research Laboratory (NRL) in Washington, DC participates in the CF3 program by providing the Tiny Ionospheric Photometer (TIP, Space Science Division) and Tri-Band Beacon (TBB, Plasma Physics Division) experiments to UCAR, contributing data and algorithms to the *COSMIC* Data Analysis and Archive Center, and incorporating *COSMIC* data into new ionospheric models.

Prior to the launch of the *COSMIC* constellation, ionospheric measurements carried out using radio occultation showed that electron density gradients in the ionosphere can cause significant errors, ~30%, in the electron density profiles produced by direct inversion of the radio occultation measurements [Hajj et al., 1994]. The TIP instruments were proposed and developed to measure the electron density gradients needed to correct the electron density profiles. However, in addition to demonstrating higher accuracy electron density profiles derived from radio occultation data in conjunction with TIP measurements, these small instruments set a new sensitivity standard for ultraviolet (UV) remote sensing and broke new ground in remote sensing of ionospheric irregularities, travelling ionospheric disturbances, and forcing of the Earth's ionosphere by atmospheric tides.

2.0 TIP Instrument

2.1 *Ionospheric Nightglow*

To understand how TIP operates and why it is only used at night a brief introduction to the ionosphere and the ultraviolet radiation it emits is needed. During the daytime, solar extreme ultraviolet radiation ionizes the neutral atmosphere, building up the F-region ionosphere, which is dominated by O^+. Collisional processes simultaneously produce neutral O atoms through the dominant O^++e recombination process and the slower O^++O^- neutralization processes [Tinsley and Bittencourt, 1975]. After sunset photoionization ceases and the recombination processes dominate and lead to the nighttime decay of the ionosphere. An important feature of the recombination process is that the neutral O atoms are produced in energetically excited electron states, which decay radiatively to produce ground state atoms. This decay produces a number of emission features, including strong, (mostly) optically thin OI 135.6, 135.8 nm doublet emission and the optically thick O I 130.4 nm triplet emission in the far-ultraviolet. These multiplets are unresolved by TIP. As the 130.4 nm emission is optically thick and difficult to interpret, it is attenuated through the use of a heated crystalline filter.

The nighttime 135.6 nm emission shows contributions due to radiative recombination and O^+–O^- neutralization [Tinsley and Bittencourt, 1975], where the volume emission rate, $\varepsilon_0(z)$, for the emission is given by:

$$\varepsilon_0(z) = \gamma\ \beta_{1356} \frac{k_1 k_2 n_e(z) n_O(z) n_{O^+}(z)}{k_2 n_{O^+}(z) + k_3 n_O(z)} + \gamma\ \alpha_{1356} n_e(z) n_{O^+}(z) \tag{1}$$

where γ is the branching ratio for the 1356 or 1358 Å line (0.791 and 0.209, respectively, [Meier, 1991]), α_{1356} is the radiative recombination rate 7.5×10^{-13} cm^{-3} s^{-1} [Melendez-Alvira et al., 1999], β_{1356} is the fraction of neutralizations that produce 135.6 nm photons, 0.54, and the coefficients k_1 k_2, and k_3 are 1.3×10^{-15}, $1. \times 10^{-7}$, and 1.4×10^{-10}, respectively, all in units of cm^3 s^{-1} [Tinsley and Bittencourt, 1975]. Thus, the 135.6 nm radiance is given by:

$$4\pi I = 10^{-6} \int_0^\infty \varepsilon_0(z) dz$$

where the factor 4π indicates that the radiance indicates the number of photons emitted into 4π steradians and the factor of 10^{-6} converts from photons to megaphotons, the natural unit for Rayleighs. The ionospheric recombination signature is also present during the daytime. However, the far-ultraviolet dayglow is dominated by photoelectron impact excited emissions from atomic oxygen and molecular nitrogen [Meier, 1991] and, thus, the recombination signature cannot be extracted from the neutral atom emissions. While an alternative means for daytime ionospheric sensing using the 83.4 nm emission of O^+ [Dymond, 2008] has been developed and tested, the compact size and simplicity required for the TIP instrument forced a nighttime only design.

2.2 *TIP Description*

The TIP instrument (Figure 2000s.8.1) is composed of two modules: the photometer head or TIP Sensor Assembly (TSA) and the TIP Interface and Control Electronics (TICE). The TICE contains a compact radiation-hardened microprocessor, power supply card, and photometer and satellite telemetry interfaces. The TIP photometer consisted of a Hamamatsu subminiature (about the size of a human thumb) photomultiplier tube, with a magnesium fluoride window and a cesium iodide photocathode, which sat at the prime focus of an off-axis parabolic telescope mirror. A heated strontium fluoride filter placed just before the entrance window of the photomultiplier attenuated

wavelengths shorter than 132.5 nm and the photocathode's long wavelength response limited the instrument's passband to ~132.5-160 nm. The instrument also included a filter wheel/shutter assembly to measure the dark count of the photomultiplier and to inset pinhole apertures and a barium fluoride window into the light path. The TSA and TICE were 6×6×6 in^3 boxes and the total weight including harnessing was ~1.2 kg. further details of the instrument design and performance are found in Kalmanson et al. [2004], Budzien et al., [2009], and Dymond et al. [2009a, 2009b]. The TIP instruments cost ~$1.65 M to build and were funded by the University Corporation for Atmospheric Research (~75%) and by the Office of Naval Research (~25%). The first flight instrument was delivered ~7 months after contract initiation and the remaining 5 were delivered ~3 months later.

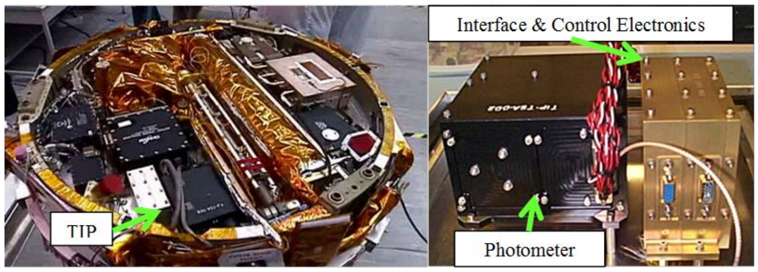

Figure 2000s.8.1 - The left hand panel shows an internal view of a CF3 satellite with the TIP indicated. The right panel shows the TIP photometer head and interface and control electronics. The photometer head is approximately 6×6×6 in^3. The total instrument and electronics mass is ~1.2 kilograms (credit: NRL).

3.0 Key Scientific Results

In addition to demonstrating tomography using the TIP and GOX measurements [Dymond et al., 2009b], which was the principal reason for flight of the TIP, there have been additional NRL-authored publications resulting from the *COSMIC* measurements.

1. Characterization of Ionospheric Structure in the Equatorial Ionization Anomaly (EIA) (Figure 2000s.8.2): Measurements of the radiance in the EIA made by three TIP instruments (1, 3, and 5) during the early mission are shown [Coker et al., 2009]. Each vertical band in the figure denotes a TIP orbit. The wave-4 pattern driven by tropospheric tides is clearly evident in the modulation of the EIA crests about the magnetic equator. Small dark bands across the TIP orbit passes indicate the presence of ionospheric irregularities. The signal-to-noise ratio in these images is very high with <1% error bars near the EIA peaks.

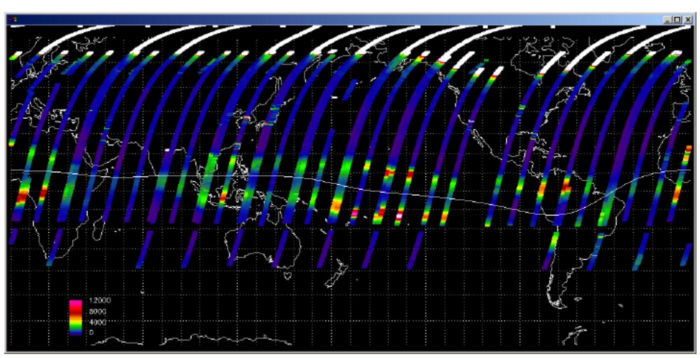

Figure 2000s.8.2 - A count rate map (0-12000 corresponding to 0-20 Rayleigh signals) of TIP nighttime measurements at ~21 Hr Local Time on Sept. 14, 2006 is shown. The measurement uncertainties near the peak intensities are less than 1%. Each strip indicates the radiance measured along the orbit planes of the CF3 satellites. The wavy white line running horizontally across the center of the map is the magnetic equator. The wavy green-red areas near the magnetic equator indicate the Equatorial Ionization Anomaly (EIA). The

varying distance between the EIA peaks and the magnetic equator is caused by an interaction between atmospheric tides propagating upward from the troposphere and the dynamo currents that drive the vertical uplift of plasma in the low latitude ionosphere. Ionospheric irregularities can be seen as narrow dark bands on many of the orbits (credit: NRL).

<u>First Observation of a Medium Scale Travelling Ionospheric Disturbance from Space</u> (Figure 2000s.8.3): The Combined Radio Interferometry and COSMIC Experiment in Tomography (CRICKET) campaign occurred in September 2007 and was designed to use the *COSMIC* ionospheric measurements made during an over-flight in conjunction with ionospheric measurements made using the Very Large Array (VLA) radio telescope near Socorro, NM to study regional structures that affect VLA observations. During the campaign, a Medium-Scale Travelling Ionospheric Disturbance (MSTID) was observed by both the *COSMIC* instruments and the VLA. This is the first observation of a MSTID from space and provides a pathfinder for the use of space-based, high sensitivity UV measurements for studying the global distribution of MSTIDs [Dymond et al., 2011].

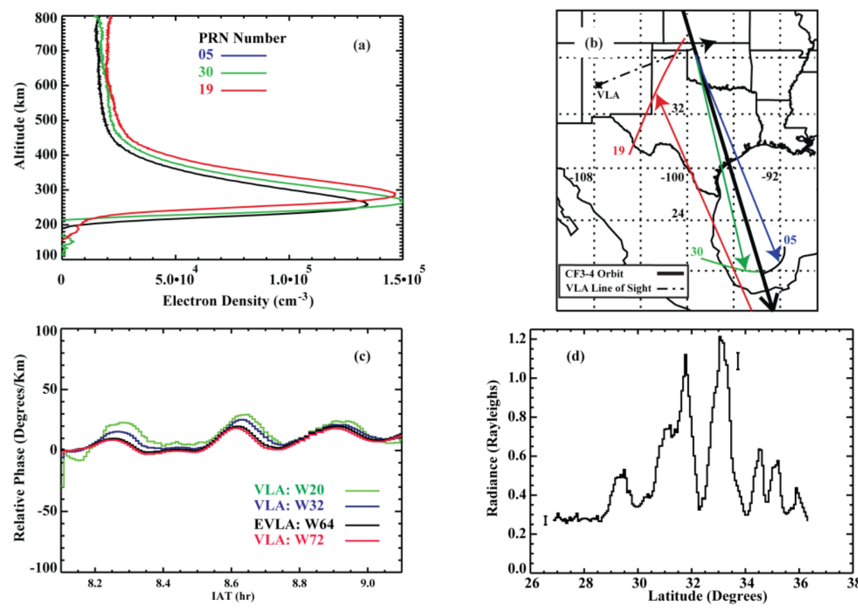

Figure 2000s.8.3 - CRICKET Campaign Measurements. Panel (a) shows the electron density profiles from three GOX occultations in the American sector. Panel (b) shows the satellite orbit and the tangent point trajectories for the occultations with the VLA location indicated by the "". The occultation lines-of-sight are indicated by the colored arrows. The CF3 satellite moved from north to south as indicated by the large arrow on the orbit. Panel (c) shows the baseline reduced phases along the Southwestern arm of the VLA. Panel (d) shows the observed TIP radiances with representative ±2-σ error bars to indicate the precision of the measurements. [Dymond et al., 2011] (credit: NRL).*

4.0 Key Personnel

The TIP team at NRL included NRL Space Science Division scientists Dr. K. F. Dymond, Dr. S. A. Budzien, Mr. C. Coker, Mr. A. C. Nicholas, and Dr. D. H. Chua. The mechanical design was performed by P. C. Kalmanson (then with Praxis, Inc.) with mechanical support provided by E. Wagner (now in the Remote Sensing division at NRL). The high voltage power supply and pulse amplifier discriminator circuits were designed by Dr. K. D. Wolfram of the NRL Naval Center for Space Technology. The electronics were designed and manufactured at Silver Engineering Inc., in Melbourne, FL under the direction of G. Clifford, lead engineer.

References: 2000s.8: The Tiny Ionospheric Photometer (TIP) for the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC)

Anthes, R. A., P. A. Bernhardt, Y. Chen, L. Cucurull, K. F. Dymond, D. Ector, S. B. Healy, S.-P. Ho, D. C. Hunt, Y.-H. Kuo, H. Liu, K. Manning, C. McCormick, T. K. Meehan, W. J. Randel, C. Rocken, W. S. Schreiner, S. V. Sokolovskiy, S. Syndergaard, D. C. Thompson, K. E. Trenberth, T.-K. Wee, N. L. Yen, and Z. Zeng (2008), "The *COSMIC/FORMOSAT-3* Mission: Early Results", Bull. Amer. Meteor. Soc., 313-333, DOI:10.1175/BAMS-89-3-313.

Budzien, S. A., K. F. Dymond, C. Coker, D. H. Chua, and J.-Y. Liu (2009), "Tiny Ionospheric Photometer Experiment aboard *FORMOSAT-3/COSMIC*", Solar Physics and Space Weather Instrumentation III. Edited by Fineschi, Silvano; Fennelly, Judy A. Proceedings of the SPIE, 7438, pp. 743813-743813-11, doi: 10.1117/12.826532.

Coker, C., K. F. Dymond, S. A., Budzien, D. H. Chua, J.-Y. Liu, D. N. Anderson, Su. Basu, and T. R. Pederson (2009), "Observations of the Ionosphere using the Tiny Ionospheric Photometer", Terr. Atmos. Ocean. Sci., 20, 227-235, No. 1, doi: 10.3319/TAO.2008. 01.18.02 (F3C).

Dymond, K. F. (2008), "A New Algorithm for Sensing the Global Daytime Ionosphere from Space", Proceedings of the 12th International Ionospheric Effects Symposium(IES2008), JMG Associates Ltd., Alexandria, VA, May 13-15, pp 442-449.

Dymond, K. F., S. A. Budzien, C. Coker, and D. H. Chua (2009a), "On-orbit Calibration of the Tiny Ionospheric Photometer on the *COSMIC/FORMOSAT-3* Satellites", Solar Physics and Space Weather Instrumentation III. Edited by Fineschi, Silvano; Fennelly, Judy A. Proceedings of the SPIE, 7438, pp. 743814-743814-11, doi: 10.1117/12.825316.

Dymond, K. F., Budzien, S. A., C. Coker, D. H. Chua, and J.-Y. Liu (2009b), "Tomographic Reconstruction of the Low-latitude Nighttime Electron Density Using *FORMOSAT-3/COSMIC* Radio Occultation and UV Photometer Data", Terr. Atmos. Ocean. Sci., 20, 215-226, No. 1, doi: 10.3319/TAO.2008.01.15.01(F3C).

Dymond, K. F., C. Watts, C. Coker, S. A. Budzien, P. A. Bernhardt, N. Kassim, P. Ray, T. J. Lazio, K. Weiler, P. C. Crane, P. S. Ray, A. Cohen, T. Clarke, L. J. Rickard, G. B. Taylor, F. Schinzel, Y. Pihlstrom, M. Kuniyoshi, S. Close, P. Colestock, S. Myers, and A. Datta (2011), "A Medium-Scale Traveling Ionospheric Disturbance Observed from the Ground and from Space", Radio Sci., 46, RS5010, doi:10.1029/2010RS004535.

Hajj, G. A., Ibanez-Meier, E. R., Kurzinski, E. R., and Romans, L. J. (1994), "Imaging the Ionosphere with the Global Positioning System", Internat. J. of Imag. Syst. and Tech., 5, 174–184. Kalmanson P. C., S. A. Budzien, C. Coker, and K. F. Dymond, "The Tiny Ionospheric Photometer Instrument Design and Operation", Instruments, Science, and Methods for Geospace and Planetary Remote Sensing, edited by Carl A. Nardell, Paul G. Lucey, Jeng-Hwa Yee, James B. Garvin, Proceedings SPIE **5660**, 259, 2004.

Meier, R. R. (1991), "Ultraviolet Spectroscopy and Remote Sensing of the Upper Atmosphere", Space Sci. Rev., 58.

Melendez-Alvira, D. J., Meier, R. R., Picone, J. M., Feldman, P. D., and McLaughlin, B. M. (1999) "Analysis of the Oxygen Nightglow Measured by the Hopkins Ultraviolet Telescope: Implications for Ionospheric Partial Radiative Recombination Rate Coefficients", J. Geophys. Res., 104, 14901-14913.

Tinsley, B. A., and J. A. Bittencourt (1975), "Determination of F Region Height and Peak Electron Density at Night Using Airglow Emissions from Atomic Oxygen", J. Geophys. Res., 80, 2333–2337.

2000's.9: The NRL Atmospheric Neutral Density Experiment (ANDE)

Contributed by Andrew W. Nicholas

1.0 Introduction

The Naval Research Laboratory has developed a satellite suite to improve precision orbit determination and prediction by monitoring total atmospheric density between 300 and 400 km. The key developers at NRL were Andrew Nicholas (NRL/SSD), Stefan Thonnard (NRL/SSD) and Marc Davis (NRL Naval Center for Space Technology). The suite, known as the *Atmospheric Neutral Density Experiment* (*ANDE*)[1,2], consists of a series of four micro satellites with instrumentation to perform two interrelated mission objectives. First, provide high quality satellites with stable and well-determined coefficients of drag to calibrate techniques and models for precision orbit determination. Second, provide detailed atmospheric composition to validate new ultraviolet remote sensing techniques. The DoD Space Test Program provided launch services and deployment into orbit for two missions, each mission flying a pair of *ANDE* spacecraft. The *Atmospheric Neutral Density Experiment Risk Reduction* (*ANDERR*)[3] mission was launched on Dec. 9, 2006 onboard the STS-116, Space Shuttle Discovery, and deployed (as seen in Figure 2000s.9.1) into orbit on Dec. 21, 2006. The *ANDE2* mission was launched on July 15, 2009 onboard the Space Shuttle Endeavour, STS-127, and deployed (as seen in Figure 2000s.9.1) into orbit on July 30, 2009. The four *ANDE* spacecraft have since decayed and are no longer in orbit. The two *ANDERR* spacecraft, MAA and FCal, re-entered on December 25, 2007 and May 25, 2008. The two *ANDE2* spacecraft, Castor and Pollux, re-entered on March 28, 2010 and August 18, 2010. This paper will focus on the analysis of drag data from both flights, which is based on radar observations and optical observations of the retro-reflectors on each satellite via satellite laser ranging (SLR). The international laser ranging service (ILRS)[4] tracked the satellites and amateur HAM radio enthusiasts provided telemetry acquisition; the *ANDE* data set is extensive. The *ANDE* spacecraft were designed, built, tested, flown and operated, and data sets analyzed by NRL.

2.0 Mission Objectives

The two *ANDE* satellite suites (*ANDERR* and *ANDE2*) consist of two nearly perfect spherical micro-satellites with instrumentation to perform two interrelated mission objectives. The primary *ANDE2* mission objectives are to measure the variability of atmospheric density driven by solar and geomagnetic forcings for improved orbit determination and to provide a test object for the US space surveillance network (SSN). A joint effort between the Space Science Division and the Naval Center for Space Technology to routinely process and analyze the *ANDE* data has led to improved orbit determination and prediction using an atmospheric model correction method. The *ANDE* data provide a valuable tool for correcting deficiencies in atmospheric models and have led to advancements in miniature sensor technology. These advancements are pivotal for multi-point in-situ space weather sensing and led to the development of the NRL/SSD's Winds Ions Neutrals Composition Suite (WINCS), a compact suite of in-situ sensors to measure neutral winds, ion drifts, temperature, density and composition of both ions an neutral species.

The major source of error in determining the orbit of objects in Low Earth Orbit (LEO), altitudes less than 1000 km, is the computation of acceleration due to atmospheric drag. This acceleration is governed by the equation,

$$a_d = -\frac{1}{2}B\rho v^2 \qquad (1)$$

where a_d is the acceleration, ρ is the atmospheric density and v is the orbital velocity relative to the medium (including cross-track and radial velocities). The ballistic coefficient[5], B, is given by

$$B = \frac{C_D A}{m} \quad (2)$$

with C_D being the coefficient of drag, A the projected frontal area and m the mass of the object. The constant and well-determined cross section and surface properties of the *ANDE* spherical spacecraft provide an ideal set of objects for monitoring atmospheric drag and the calibration of SSN assets.

The technique to derive the total atmospheric density from radar and optical observations of the *ANDERR* spacecraft is described in detail by Nicholas et al. (2007)[6]. The entire *ANDERR* data set was analyzed with this method using the NRL Mass Spectrometer Incoherent Scatter Radar Extended, NRLMSISE-00, model[7]; see Essay 90s.6 for a discussion about MSIS. The *ANDE* data provide a body of measurements which showed an over-specification of total density by climatology models that was in agreement with the findings of Emmert and Picone[8], who have shown a consistent decrease in thermospheric density of the past three decades.

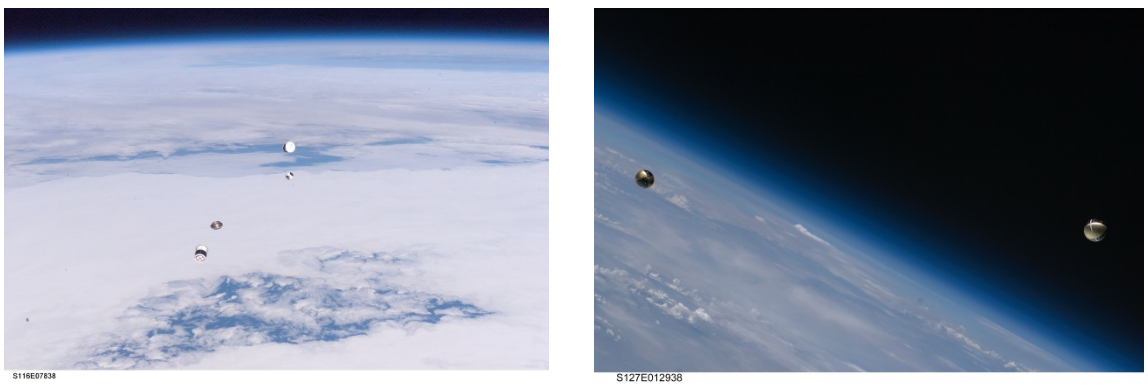

Figure 2000s.9.1 - The deployment of the Atmospheric Neutral Density Experiment Risk Reduction (ANDERR) spacecraft on December 21, 2006 during the STS-116 mission (left). The deployment of the Atmospheric Neutral Density Experiment Risk Reduction (ANDE2) spacecraft on July 30, 2009 during the STS-127 mission (right) (credit: NASA).

The *ANDE* spacecraft as-flown mass and size properties are summarized in Table 2000s.9.1[13,14]. Each of the *ANDE* spacecraft was modeled[7] resulting in a modeled C_D value of 2.112 with a standard deviation of 0.008 for the *ANDERR* Mock *ANDE* Active (MAA) and both *ANDE2* spacecraft. The average value for the modeled FCal C_D is 2.111 with a standard deviation of 0.008.

Table 2000s.9.1. *ANDE* Spacecraft Properties

Spacecraft	Diameter (m)	Mass (kg)	A/m (m^2/kg)	C_D (modeled)
ANDERR MAA	0.4826	52.04	0.0035	2.112
ANDERR FCal	0.4445	62.70	0.0025	2.111
ANDE2 Catsor	0.4826	47.45	0.0039	2.112
ANDE2 Pollux	0.4826	27.44	0.0067	2.112

3.0 *ANDE* Data Processing and Analysis

Version 5.01 of the NRL Orbit Covariance Estimation and Analysis (OCEAN)[17] orbit determination code was configured to make weighted least squares estimates of the initial conditions and the scale factor for the drag model. The observation data were sampled at 48-hour intervals (beginning in the

middle of a day) and the fit and prediction final ephemeris was produced. The observation data were corrected for known biases (and center of mass) and weighted using past sensor performance values so that the SLR data naturally biases the solutions toward reality in the hybrid SSN and SLR runs. The high fidelity force models including either EGM-96 or GGM02C at degree and order 70x70, the ocean tides, the MSIS density models, the HWM93 thermospheric winds, and all International Earth Rotation and Reference System (IERS) conventions frames and displacement typical for accurate SLR processing.

A comparison between the resulting MAA C_D and FCal C_D from the OCEAN run, using NRL MSISE2000 and a priori area and mass information, yields excellent agreement between the two objects even as the altitude separation between the two spacecraft increases due to differential drag. The average C_D value for both missions are summarized in Table 2000s.9.2. These CD results are clearly non-physical as seen from Eq. (1), as the value is well below 2.0. The NRLMSISE-00 and Jacchia 70 models are over-estimating the atmospheric density by about 25% on average and the OCEAN code is correcting for this by scaling the B term down. This over-estimation of the thermospheric density is in direct agreement with the findings of Emmert and Picone[8]. The density correction factors as a function of time are plotted in Figure 2000s.9.2.

Table 2000s.9.2. *ANDE* mission average C_D and density correction factors

	MSIS			J70		
Object/Year	**Avg. C_D**	**Std. Dev.**	**Scale**	**Avg. C_D**	**Std. Dev.**	**Scale**
Castor '09	1.454	0.176	0.689	1.705	0.227	0.807
Pollux '09	1.445	0.171	0.684	1.680	0.236	0.796
MAA '07	1.690	0.156	0.802	1.727	0.248	0.818
FCal '07	1.676	0.170	0.795	1.720	0.276	0.811

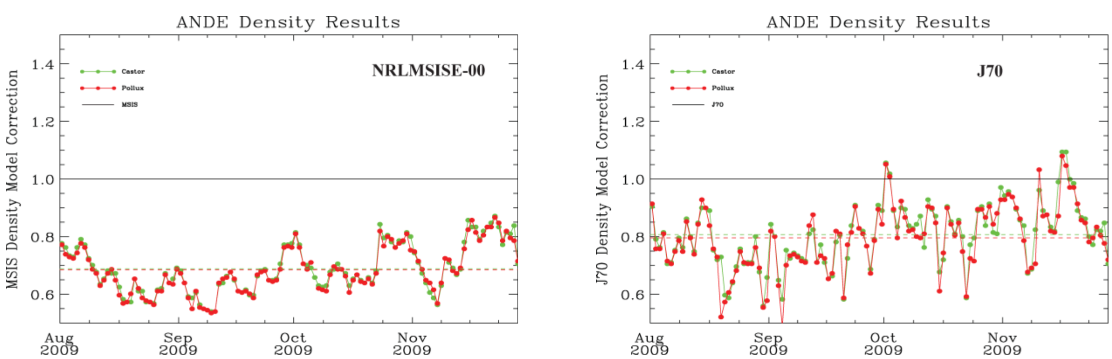

Figure 2000s.9.2 - ANDE2 Density correction factors, MSIS (left) and J70 (right). The dashed lines represent the average for the time period shown (credit: NRL).

Note that the J70 results have a consistent scaling factor of about 0.8 during both the *ANDERR* and the *ANDE2* missions, while the MSIS results differ; 0.80 for the *ANDERR* mission and 0.69 for the *ANDE2* mission. The MSIS results have much lower standard deviations than the J70 results. The *ANDE2* derived C_D using MSIS and J70 for each spacecraft, the altitude of each spacecraft, the retrieved density, the F10.7 cm radio flux, geomagnetic Ap index, and the NASA *Advanced Composition Explorer* (*ACE*) satellite solar wind velocity as a function of time. To gain insight into the difference between the MSIS and J70 results from the *ANDE2* mission the correction factor was plotted as a function of the solar driver proxy (F10.7 cm flux) and geomagnetic driver proxy (Ap index). During the extremely low activity observed during the latter half of 2009, the solar and geomagnetic inputs both drive MSIS in the direction towards a more severe correction but drive J70 in opposite direction.

4.0 Major Science Results

It is clear that the *ANDE* spacecraft are useful calibration targets due to their well-characterized size and shape. The SLR observations performed by the members of the ILRS have been used to augment the radar data to constrain the accuracy and stability of the estimated ballistic coefficient and to assess the accuracy of the predictions with absolute confidence. These results are based upon four *ANDE* spacecraft, which are at different altitudes as the missions progressed. The data show a consistent over estimation of the density by the NRLMSISE-00 model by an average of 26.6% for the *ANDERR* mission and 45.1% for portions of the *ANDE2* mission. The over specification of total density is in agreement with the findings of Emmert and Picone[8], who have shown a consistent decrease in thermospheric density of the past three decades. The analysis of the data using the J70 model showed similar results from both the *ANDERR* and the *ANDE2* missions; although the behavior of the J70 model at the extremely low activity in 2009 appeared to compensate by balancing the thermospheric response to extremely low solar flux with its response to prolonged extremely low geomagnetic activity. These spacecraft provide ideal calibration targets for observation assimilative models such as the High Accuracy Satellite Model (HASDM) and Jacchai-Bowman 2008 (JB08).

The analysis technique applied to the *ANDERR* data set separates geomagnetic forcing of the atmosphere from solar irradiance forcing of the atmosphere. The analysis confirms that Co-rotating Interaction Regions (CIRs) with short term 5-,7-,9- day oscillations similar to those observed with CHAllenging Minisatellite Program (CHAMP) in 2005[19,20] persisted into the first half of 2007 and were observable in the *ANDERR* data at lower altitudes than observed by CHAMP. Moreover, although the inclination of the *ANDERR* satellites is only 51.2° we observe geomagnetic forcing effects at these mid- to low-latitudes that were seen in the polar orbiting (87.3°) CHAMP data.

The MSIS model is not properly capturing the effect of geomagnetic forcing (especially at the low end of the solar/geomagnetic forcing range), as correlations are evident in the fitted C_D values with the geomagnetic Ap index and the solar wind velocity at short periods of 5-, 7-, and 9-days. MSIS is also not capturing the 18-day period observed to correlate with the F10.7 cm flux data. The analysis of the SOLAR EUV Experiment (SEE) irradiance data did not yield significant oscillations below the 27-day solar rotation period.

- Fitted *B* values of the *ANDE* data show that both the MSIS & J70 model are over estimating the atmospheric density by 25 - 45% in the 250 - 330 km altitude range.
- Runs from both models show correlation of the retrieved B with atmospheric drivers (solar and geomagnetic)
- Periodicities were observed in the drag-derived ρ residuals and the atmospheric drivers during 2007 solar minimum
    - 27-day periods were observed in ρ residuals and with all drivers ($F_{10.7}$, Ap, V_{sw}, SEE_{irr})
    - 18-day period was observed in ρ residuals and $F_{10.7}$
        - ρ residuals response is time lagged from $F_{10.7}$
    - 9-day periods were observed in ρ residuals and geomagnetic drivers (Ap, V_{sw})
- Technique allows one to separate solar irradiance forcing from geomagnetic forcing.
- This research advanced miniature sensor technology that was pivotal to the development of the WINCS in-situ sensor suite.

References: 2000s.9: The NRL Atmospheric Neutral Density Experiment (ANDE)

[1]Nicholas A.C., et al., “The Atmospheric Neutral Density Experiment (*ANDE*)” Proceedings of the 2002 AMOS Technical Conference, Maui HI, Sept. 2002.

[2]Nicholas A.C,, Gilbreath G.C., Thonnard S.E., Kessel R.A., Lucke R., Sillman C.P., “The atmospheric neutral density experiment (*ANDE*) and modulating retroreflector in space (MODRAS): combined flight experiments for the space test program” Proc. SPIE Vol. 4884, p. 49-58, Optics in Atmospheric Propagation and Adaptive Systems V; Anton Kohnle, John D. Gonglewski; Eds., March 2002.

[3]Nicholas A.C., Thonnard S.E., Galysh I., Kalmanson P., Bruninga B., Kelly H., Ritterhouse S., Englehardt J., Doherty K., McGuire J., Niemi D., Heidt H., Hallada M., Dayton D., Ulibarri L., Hill R., Gaddis M., Cockreham B., “An Overview Of The *ANDE* Risk Reduction Flight”, Proceedings of the AMOS Technical Conference, Maui, HI., Sept. 2002.

[4]Pearlman, M.R., Degnan, J.J., and Bosworth, J.M., "The International Laser Ranging Service", Advances in Space Research, Vol. 30, No. 2, pp. 135-143, July 2002.

[5]Vallado D. and Carter S., “Accurate Orbit Determination from Short-Arc Dense Observational Data”, Paper AAS 97-704, AAS/AIAA Astrodynamics Specialist conference, Sun Valley, Idaho, Aug 4-7, 1997.

[6]Nicholas A.C., J. M. Picone. J. Emmert. J. DeYoung, L. Healy, L. Wasiczko. M. Davis, C. Cox, “Preliminary Results from the Atmospheric Neutral Density Experiment Risk Reduction Mission”, Proc. of the AAS/AIAA Astrodynamics Specialist Conference, paper #AAS 07-265, Mackinac Island, MI, Aug 20-24, 2007.

[7]Picone J.M., Hedin A.E., Drob D.P., and Aikin A.C., “NRLMSISE-00 Empirical Model of the Atmosphere: Statistical Comparisons and Scientific Issues,” *J. Geophys. Res.*, (2001).

[8]Emmert J.T., Picone J.M., Lean J.L., Knowles S.H., Global change in the thermosphere: Compelling evidence of a secular decrease in density, J. Geophys. Res., 109, A02301, doi:10.1029/2003JA010176, 2004.

[9]Cox, C.M., and Lemoine F.G., Precise Orbit Determination of the Low Altitude Spacecraft TRMM, GFZ-1, and EP/EUVE Using Improved Drag Models, Paper AAS 99-189, presented at the AAS/AIAA Space Flight Mechanics Meeting, Breckenridge, Colorado, February, 1999.

[10] Nicholas A.C., Finne T., Davis M.A., “Atmospheric Neutral Density Experiment Risk Reduction (*ANDERR*) Flight Hardware Details”, http://ilrs.gsfc.nasa.gov/docs/anderr_hw.pdf, 2007.

[11]Soyka M., Middour J., Binning P., Pickard H., Fein J., "The Naval Research Laboratory's Orbit / Covariance Estimation and Analysis Software: OCEAN", Proceedings of AAS/AIAA Astrodynamics Meeting, pp1567 -1586, Sun Valley, Idaho, 1997.

[12]Lei, J., Thayer J.P., Forbes J.M., Sutton E.K., and Nerem R.S., Rotating solar coronal holes and periodic modulation of the upper atmosphere, Geophys. Res. Lett., 35, L10109,2008.

[13]Thayer, J. P., Lei J., Forbes J. M., Sutton E. K., and Nerem R. S., Thermospheric density oscillations due to periodic solar wind high-speed streams, J. Geophys. Res., 113, A06307, 2008

A1. **List of Terms and Acronyms**

2000s Decade

- SECCHI - Sun Earth Connection Coronal and Heliospheric Investigation
- STEREO - Solar TErrestrial Relations Observatory
- EIS - Extreme-ultraviolet Imaging Spectrometer
- LAT - Large Area Telescope
- DOE - Department of Energy
- MISTI - Mobile Imaging and Spectroscopic Threat Identification
- RAIDS - Remote Atmospheric and Ionospheric Detection System
- EUV - Extreme ultraviolet
- SHIMMER - Spatial Heterodyne Imager for Mesospheric Radicals
- STP - Space Test Program
- TIP - Tiny Ionospheric Photometer
- COSMIC - Constellation Observing System for Meteorology, Ionosphere, and Climate
- ANDE - Atmospheric Neutral Density Experiment
- NOGAPS-ALPHA - Navy Operational Global Atmospheric Prediction System-Alpha

2000s.1

- CGRO - Compton Gamma Ray Observatory
- EGRET - Energetic Gamma Ray Experiment Telescope
- GLAST - Gamma-ray Large Area Space Telescope
- SSD – Space Science Division
- SLAC - Stanford Linear Accelerator Center
- DOE - Department of Energy
- LAT - Large Area Telescope
- GBM - Gamma-ray Burst Monitor
- SED - Spacecraft Engineering Department
- AGN - Active Galactic Nuclei
- SNR - Supernova remnant
- MSP - Millisecond pulsars
- FSRQ - Flat Spectrum Radio Quiet
- BL Lac - BL Lacertae
- GRB – Gamma Ray Burst

2000s.2

- MISTI - Mobile Imaging and Spectroscopic Threat Identification
- WMD - Weapons of mass destruction
- DoD - The Department of Defense
- NRL - Naval Research Laboratory
- OSSE - Oriented Scintillation Spectrometer Experiment
- CGRO - COMPTON Gamma-Ray Observatory
- DNDO - Domestic Nuclear Detection Office
- SORDS - Stand-Off Radiation Detection Systems
- COTS - Commercial off-the-self
- NRC - National Research Council

2000s.3

- STEREO - Solar Terrestrial Relations Observatory

- CMEs - Coronal Mass Ejections
- STDT - Science and Technology Definition Team
- SWAVES - STEREO/Waves
- SECCHI - Sun Earth Connection Coronal and Heliospheric Investigation
- IMPACT - In-situ Measurements of Particles and CME Transients
- SEP - Solar energetic particle
- PLASTIC - Plasma and Suprathermal Ion Composition
- CMEWS - Coronal Mass Ejection Warning System
- EUVI - Ultraviolet telescope
- CIR - Corotating Interaction Region

2000s.4

- EIS - Extreme-ultraviolet Imaging Spectrometer
- EUV - extreme-ultraviolet
- BCS - Bragg Crystal Spectrometer
- AO - Announcement of Opportunity
- GSFC - Goddard Space Flight Center
- MSSL - Mullard Space Science Laboratory
- HRTS - High Resolution Telescope and Spectrograph
- CCD – Charge-coupled device
- SOT - Solar Optical Telescope
- XRT - X-ray Telescope
- RAL - Rutherford Appleton Laboratory
- FIP - first ionization potential
- EIT - Extreme-ultraviolet Imaging Telescope

2000s.5

- SHIMMER - Spatial Heterodyne IMager for Mesospheric Radicals
- MAHRSI - Middle Atmosphere High Resolution Spectrograph Investigation
- CRISTA-SPAS – Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere-Shuttle Pallet Satellite
- SHS - Spatial Heterodyne Spectroscopy
- UV - Ultraviolet
- STP - Space Test Program
- ESPA - EELV Secondary Payload Adapter
- PMC - Polar Mesospheric Cloud
- NOGAPS-ALPHA
- DASH - Doppler Asymmetric Spatial Heterodyne
- CCD - Charge Coupled Device
- FPS - Fabry-Pérot spectrometers

2000s.6

- NWP - Numerical weather prediction
- NEPRF - Naval Environmental Prediction Research Facility
- NOGAPS - Navy Operational Global Atmospheric Prediction System
- GCM - General circulation model
- FNOC - Fleet Numerical Oceanographic Center
- R&D - Research and development
- NOARL - Naval Oceanographic and Atmospheric Research Laboratory

- MMD - Marine Meteorology Division
- NRL – Naval Research Laboratory
- MVOI - Multivariate optimum interpolation
- FNMOC - Fleet Numerical Meteorology and Oceanography Center
- NAVDAS – NRL Atmospheric Variational Data Assimilation System
- HALE - High-altitude long-endurance
- CBNR - Chemical, biological, nuclear and radiological
- MMD - Marine Meteorology Division
- UAP - Upper Atmospheric Physics Branch
- RSP - Remote Sensing Physics
- ALPHA - Advanced-Level Physics High-Altitude
- DA - Data assimilation
- SWH - Shortwave heating
- LWC - Longwave cooling
- LTE - Local thermodynamic equilibrium
- GFS - Global Forecast System
- GWD - Gravity-wave drag
- GOATS - Global Ozone and Assimilation Testing System
- TIMED – Thermosphere Ionosphere Mesosphere Energetics and Dynamics
- NAVDAS-AR - NRL Atmospheric Variational Data Assimilation System -Accelerated Representor
- ESPC – Earth System Prediction Capability
- COA - Course of action
- NAVGEM - Navy Global Environmental Model

2000s.7

- RAIDS - Remote Atmospheric and Ionospheric Detection System
- ISS - International Space Station
- HICO - Hyperspectral Imager for Coastal Ocean
- STP – Space Test Program
- HREP - HICO-RAIDS Experiment Payload
- JEM-EF - Japanese Experiment Module Exposed Facility
- HTV - H-II Transfer Vehicle
- FUV – Far Ultraviolet
- EUV – Extreme Ultraviolet
- SPAWAR - Space and Naval Warfare Systems Command
- DMSP - Defense Meteorology Satellite Program
- ONR - Office of Naval Research
- SBUV/2 - Solar Backscatter Ultraviolet ozone instrument

- TIGERS - Thermospheric and Ionospheric Global Remote Sensing
- TIMED - Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics
- ISRO - Indian Space Research Organisation

2000s.8

- TIP - Tiny Ionospheric Photometer
- COSMIC - Constellation Observing System for Meteorology, Ionosphere, and Climate
- GPS - Global Positioning System
- TBB - Tri-band radio Beacon

- GOX - GPS Occultation Experiment
- JPL - Jet Propulsion Laboratory
- NSPO - National Space Organization
- FORMOSAT-3 - Formosa Satellite Mission #3
- UCAR - University Corporation for Atmospheric Research
- UV – Ultraviolet
- TSA - TIP Sensor Assembly
- TICE - TIP Interface and Control Electronics
- EIA - Equatorial Ionization Anomaly
- VLA - Very Large Array
- MSTID - Medium-Scale Travelling Ionospheric Disturbance

2000s.9

- ANDE - Atmospheric Neutral Density Experiment
- ANDERR - Atmospheric Neutral Density Experiment Risk Reduction
- SLR - Satellite laser ranging
- ILRS - International laser ranging service
- SSN - Space surveillance network
- WINCS - Winds Ions Neutrals Composition Suite
- LEO - Low Earth Orbit
- NRLMSISE-00 - NRL Mass Spectrometer Incoherent Scatter Radar Extended
- ANDE2 - Atmospheric Neutral Density Experiment Risk Reduction
- MAA - Mock ANDE Active
- OCEAN - Orbit Covariance Estimation and Analysis
- IERS - International Earth Rotation and Reference System
- ACE - Advanced Composition Explorer
- HASDM - High Accuracy Satellite Model
- JB08 – Jacchai-Bowman 2008
- CIRs – Co-rotating Interaction Regions
- CHAMP - CHAllenging Minisatellite Program
- SEE - SOLAR EUV Experiment